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INFLUENCE OF INDOOR AIR TEMPERATURE VARIATION ON OFFICE WORK PERFORMANCE

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Abstract. Indoor air quality as well as thermal comfort has a significant effect on productivity of the employees in office buildings. It may reduce work performance and cause financial losses in a long term perspective. Sudden temperature swings may have an impact on the work performance as well. The aim of this study was to assess the change of office work performance of the same individuals affected by unsteady air temperature.

Office work was simulated in the test chamber with two workplaces and two persons at the time. 78 individuals of age 19 to 31 were divided into three groups and took participation in performing productivity tests. Two cases were analysed: one with the temperature rise from +22 to +26 °C and another with the temperature drop from +22 to +18 °C. The same tests were performed with the placebo group under a constant air temperature of +22 °C.

Results of the study showed that subjects in the placebo group performed better while executing tasks for the second time and the overall productivity was higher by 2.1%. In case of the air temperature raise, performance reduced by 0.1% and the overall productivity improved by 5.2% in case of air temperature drop.

Keywords: unsteady air temperature, thermal sensation, human performance, laboratory tests.

Introduction

Air temperature is one of the most important parameters of indoor climate and it has significant effect on work performance. But in many office buildings, thermal conditions are not well-controlled due to insufficient heating or cooling capacity, high internal or external loads, large thermal zones, improper control or operation of the heating, ventilation and air conditioning (HVAC) equipment as well as other factors.

Building services engineers are interested in improving indoor environments and quantifying the effects. Yet potential health and productivity benefits are not generally considered while input of exploitation is calculated. Only initial investment, energy and maintenance costs are typically considered. A few studies have shown that measures improving indoor climate are cost-effective when health and productivity benefits resulting from an improved conditions are calculated (Djukanovic *et al.* 2002; Fisk 2000; Fisk *et al.* 2003, 2011; Hansen 1997; Kempinski 2003; Seppänen, Vuolle 2000; Wargocki 2003). There is an obvious need to develop tools so that economic outcomes of health and productivity can be integrated into cost-benefit calculations alongside initial investment costs, energy and maintenance costs.

Due to outdoor air temperature variations, indoor air temperature may be out of the comfort range temporarily during the work day in office buildings. Therefore, despite of the installation of modern facilities, occupants may be exposed to temporary thermal discomfort that affects their performance and productivity.

Seppänen *et al.* (2006) outlined a relation between performance and air temperature based on various productivity studies. It showed that performance increases with temperature up to +21 – +22 °C and decreases by approximately 2% per 1 °C increase of air temperature in the range of +23 – +35 °C. The maximum performance is achieved at +21.6 °C (Fig. 1).

Haneda *et al.* (2008) has presented the results of the research which revealed that both productivity and fatigue of the subjects increased at the time of the experiment. Tiredness was more intense at higher temperatures (+28.5 °C).

A study presented by Tanabe (2005) revealed that the subjects complained feeling more fatigued and higher cerebral blood flow was required to maintain the same level of task performance at hot condition than at the thermally neutral condition.

Research performed by Wyon *et al.* (1979) showed significant interaction between temperature conditions for multiplication tests which were later verified by some other studies. Tsai-Partington test was also used in the above mentioned study and the subjects achieved best results when the air temperature was +23 °C. Important trends related to the gender of the subjects were outlined. Female subjects tended to maintain

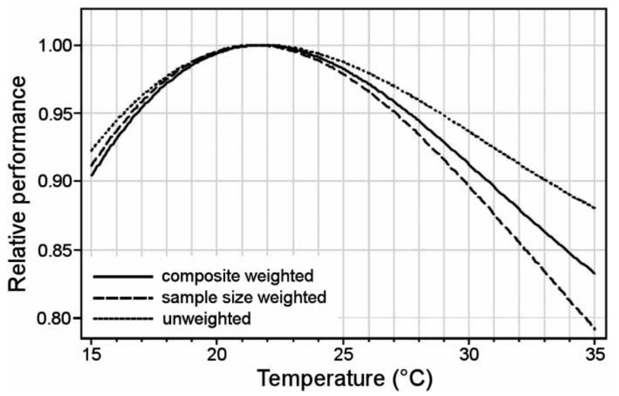

Fig. 1. Normalized relation between performance and air temperature in rooms (Seppänen *et al.* 2006)

performance at higher temperatures as they felt more comfortable in warmer environment.

Kosonen and Tan (2004) stated that task-related work performance correlates significantly with the human perception of thermal environment that in turn is dependent on temperatures. Yet, different combinations of thermal criteria (air velocity, clothing level, metabolic rate, etc.) can lead to similar PMV values, therefore it is important to document PMV during the productivity tests.

While analysing impact of air temperature on work performance, it is important to keep stable ventilation in the room with subjects. Wargocki *et al.* (2005) outlined the impact of ventilation rate on productivity of schoolchildren. The study revealed that after increasing of ventilation rate from 5 l/s per person to 10 l/s per person, performance of school-work increased by approximately 15%.

Assessment of work performance is important from both quality of life and financial point of view (Wargocki, Seppänen 2006). Yet, considering climate change and the fact that HVAC systems of buildings are not always able to ensure indoor air parameters at the required level, occupants may be exposed to temporary thermal stress due to too low or too high air temperatures.

Šeduikyte and Paukštys (2008) revealed that in 43% tested buildings with large glazed areas, temperatures were beyond the comfort range. The predicted percentage of employees satisfied with thermal environment working was not higher than 20% in tested offices.

Valančius *et al.* (2006) presented a study in the one-cell building, showing that internal air temperature might swing in the range of 4 °C in case of extreme external air temperature variation (in the range of approximately 20 °C).

The comfort air temperature range in Lithuania is regulated by the standards of hygiene. It may vary from +22 °C to +24 °C in case of performing sedentary job in the fixed workstation during the cold season, and from +23 °C to +25 °C during the warm season. Relative humidity should be in the range of 40–60%, air velocity should not exceed 0.1–0.15 m/s (HN 69:2003). No probable variations of parameters timewise are given.

Rimkus *et al.* (2006) presented climate forecast for Lithuania for XXI century according to which annual air temperature is expected to be higher by 2.3–5.7 °C till 2080. Extreme alteration is expected on February (mean temperature would rise by 3–9 °C). According to the forecast, day temperature range splay out, inrush of brief strong winter frosts will be more frequent. In the other study author prognosticated longer duration of the high sun spine during average season (Rimkus *et al.* 2007). This would be extremely perceptible during May to September. On the other hand, there would be less direct sunlight in the winter. Similar trends are observed in most parts of the world.

The outdoor climate change will undoubtedly have the effect on indoor air temperatures as the heating and cooling power of HVAC systems will not sufficient to handle the processes.

Results of all studies related to productivity and mentioned above present work performance data obtained by testing several groups of subjects. The tests are rarely performed with the same people. Yet, in order to analyse the effect of immediate air temperature swing on office work performance, the same subjects should be exposed to it.

The aim of this study was to assess the change of the office work performance and sense of comfort of the same individuals affected by unsteady air temperature.

1. Methods

In order to determine the influence of quick change of thermal environment on the productivity of the occupants, laboratory tests were performed. Office work was simulated in the test chamber (13 m^2 of floor area) with two workplaces and two persons at the time. The chamber was installed in the other room with the constant air temperature of approximately +22 °C.

Air temperature in the chamber was controlled using the air handling unit with air heating and cooling functions.

During the experiment all other indoor climate parameters except air temperature were kept stable. Ventilation rate in the chamber was 20 l/s per person and CO_2 concentration varied in the range of 450 to 600 ppm. Mixing ventilation was installed in the chamber and the average air velocity in the occupied zone was below 0,1 m/s. Background noise level was 43 ± 3 dB(A), illumination was set on 309 ± 7 lx on the table surface. As the experiment was performed in winter and early spring time, the relative humidity

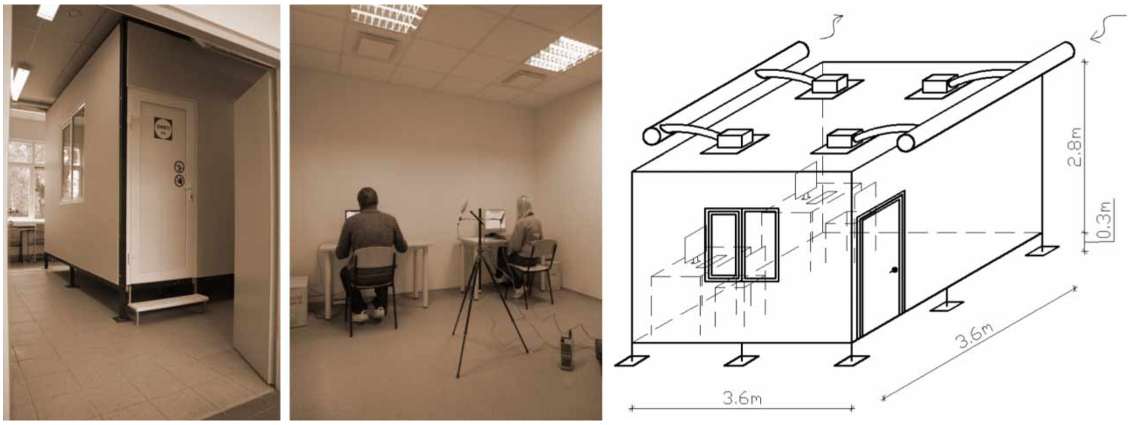

Fig. 2. View and geometry of the test chamber used in the study

indoors was approximately 40±10%. The sketch drawing and view of the test chamber is presented in Fig. 2.

78 non-smoker individuals having no clear health problems took participation in the experiment. Subjects having either higher or university education took participation in the tests. Experiment was performed during the standard working hours in order to avoid performance losses due to fatigue and tiredness. The records of 8 participants were rejected as being conspicuous from average of the results, 4 were rejected because of distraction of the participants, for example, skipped test tasks. The information about the subjects is presented in Table 1.

Subjects did not have any knowledge of the aim of the experiment or parameters planned to be changed during the course of the test. Requirements for clothing were given to the subjects in advance.

The time of the experiment was selected to be 1 hour and 45 minutes in order to avoid performance decrement because of the fatigue. The subjects were divided into three groups. A case with the temperature rise from +22 °C to +26 °C as well as case with the temperature drop from +22 °C to +18 °C was analysed. The same tests were performed with the placebo group with a steady indoor climate conditions (constant air temperature of +22 °C). In the groups' with temperature drop and rise, temperature was raised or dropped consistently by 0.1 °C per minute. In all thermal conditions, the surface temperatures were close to the air temperature. The timetable and changes of temperature are given in the Table 2.

Air temperature, related humidity as well as operative temperature and air velocity were measured in the centre of the room using the thermal comfort measurement system with data logger. Measurement range and accuracy of temperature transducer used for the measurement was 5 to 40 °C and ±0.3 °C accordingly.

Experiments were carried out during daytime. Text typing, arithmetic calculations and Tsai-Partington test (connecting scattered numbers in sequence) were performed four times each (see Table 2). Three times during the experiment, subjects were filling in questionnaires by indicating their thermal sensation, perceived air quality, humidity perception as well as referring to the SBS symptoms felt.

Standard PMV scale was used for thermal comfort evaluation, where −3 is considered very cold, 0 is considered as neutral thermal environment and +3 is considered as very hot (EN ISO 7730).

Thermal comfort monitoring system was installed in the test chamber during the tests, measuring operative temperature, air velocity and relative humidity. PMV and PPD indices were calculated by the software, using the same seven points thermal sensation PMV scale defined in EN ISO 7730 standard (EN ISO 7730:2005).

Statistical analysis of the obtained results was performed using the Paired Samples analysis with the confidence level of 95%.

Table 1. Data of the subjects participated in the experiment

	Female subjects		Male subjects
Number of the subjects	23		43
Average age of the subjects		22 years 8 month	
Average height of the subjects	170 cm (157–185 cm)		186 cm (172–200 cm)
Average weight of the subjects	60 kg (48–90 kg)		82 kg (60–115 kg)
Average clothing		0.74 clo (0,7–0,8 clo)	

Table 2. Timetable of the implementation of the experiment

Procedures		Adaptation	Questionnaires	Text typing task (x3)	Arithmetic task (x3)	Tsai-Partington test (x3)	Text typing task (x3)	Arithmetic task (x3)	Tsai-Partington test (x3)	Questionnaires	Text typing task (x3)	Arithmetic task (x3)	Tsai-Partington test (x3)	Text typing task (x3)	Arithmetic task (x3)	Tsai-Partington test (x3)	Questionnaires
Sequence		1.	2.	3.	4.	5.	6.	7.	8.	9.	10.	11.	12.	13.	14.	15.	16.
Time, min		15	2				43			1			43				1
Temperature, °C	**Group 1**			+22 °C						+22 °C – +26 °C					+26 °C		
	Group 2			+22 °C						+22 °C – +18 °C					+18 °C		
	Group 3									+22 °C							

2. Results

Results of the occupant evaluation of thermal sensation in the PMV scale is presented in Fig. 3. At the start of the experiment air temperature was set at +22 °C in order to ensure high work performance. The measured PMV value at the start of the experiment was 0 ± 0.2.

Despite the initial prediction that thermal environment at the start of the experiment should be neutral subjects felt slightly warm (average PMV value varying from +0.52 to +0.67). Placebo group hadn't felt almost any thermal sensation difference during the whole experiment and the indicated average PMV value at the end of experiment was +0.5. While temperature rise to +26 °C increased the thermal sensation to warm (PMV value +1.30) and the temperature drop to +18 °C decreased thermal sensation to slightly cold (PMV value –0.53).

The other results of the questionnaires are presented in Table 3. Main results of the experiment are given in the Fig. 4.

According to participants subjective assessment the most sudden evaluations were observed in case of the temperature rise from +22 °C to +26 °C: sense of comfort dropped by 21.4%, concentration by 26.2% and efficiency 26.0%.

Yet, according to the test results overall productivity dropped only by 0.1% in this group, which was counted as insignificant. The rise of the temperature affected arithmetic calculations most, which were performed with 2.2% more mistakes than at the start of the experiment.

The overall performance improvement in the placebo group was approximately 2.1%. It was related to better accomplishment of the Tsai-Partington test (improved by 6.7%).

Despite of the highly negative effect of temperature rise on self estimated productivity, no significant overall reduction of productivity was observed in the temperature rise group.

Overall improvement of productivity was observed in case of reduced air temperature from +22 °C to

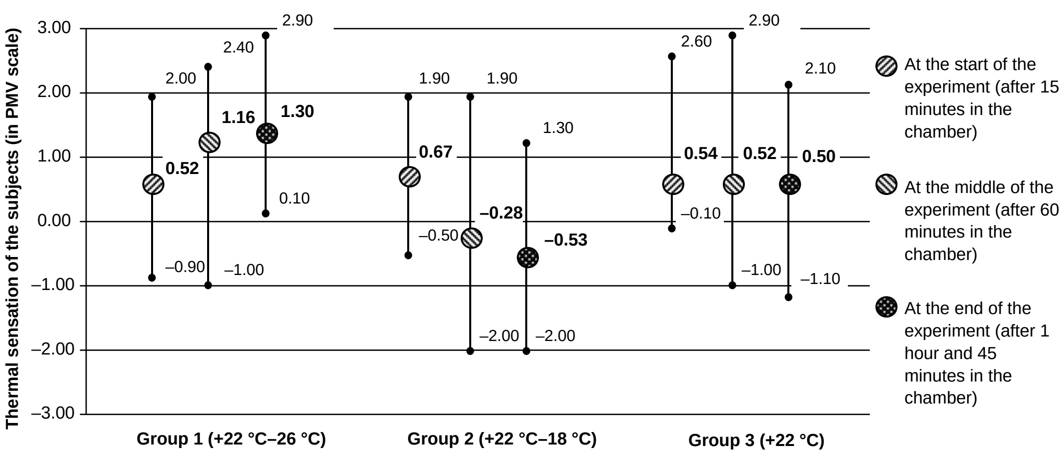

Fig. 3. Results of the evaluation of the thermal sensation in the PMV scale of the subjects

Table 3. Results of the questionnaire survey performed during the experiment (The values in the table are given in %, where 0% means the statement is totally untrue, and 100% means the statement is totally true)

	I am feeling good			I feel rested			Easy to concentrate			I am ready to work		
	At the start of the experiment	**In the middle** of the experiment	**At the end** of the experiment	**At the start** of the experiment	**In the middle** of the experiment	**At the end** of the experiment	**At the start** of the experiment	**In the middle** of the experiment	**At the end** of the experiment	**At the start** of the experiment	**In the middle** of the experiment	**At the end** of the experiment
Group 1	90.6	75.9	71.1	70.1	62.9	58.4	78.0	62.6	57.5	80.8	69.8	59.7
Group 2	81.1	73.8	74.9	72.8	67.2	62.0	73.0	64.8	60.3	86.8	75.7	66.4
Group 3	92.4	86.2	81.5	73.1	63.9	63.1	81.6	74.0	66.5	89.6	81.5	72.9

+18 °C. 5.4% less mistakes while performing the arithmetic tasks and 13.9% less mistakes while performing Tsai-Partington test were observed. Overall performance increased by 5.2% in the temperature drop group.

Influence of intermittent indoor climate had very little effect (less than 0.1%) on performance of the text typing tasks. On the other hand the text typing speed was not estimated, only errors on typed text were recorded.

Paired Samples statistical analysis was performed with the results obtained using the confidence level of 95%. Results of the analysis showed that the relationship between air temperature and work performance was not only insignificant in placebo group (as it was expected) but also in the group 1, where subjects were exposed to the air temperature rise to +26 °C. The values of significance (p-value) for the groups 1 and 3 were 0.64 and 0.10 respectively. Nevertheless the impact of air temperature drop to +18 °C on productivity was proved to be significant, with the value of significance equal to 0.00. As it was below 0.05, the increase of productivity after the air temperature drop appeared to be a reliable result. Degrees of freedom obtained by the statistical analysis were approximately 20 and the standard deviation of the overall work performance results in all three groups were 5.67.

After performing the statistical analysis of the obtained results it was clear that temperature drop from +22 °C to +18 °C has at least temporary positive effect on productivity. The number of subjects participated in this experiment was sufficient to obtain statistically significant results. Yet, this short term productivity rise differs from the most observations presented in Fig. 1. From the long term perspective, air temperature drop below +21 °C should have negative effect on productivity.

Air temperature rise from +22 °C to +26 °C did not have significant impact on productivity. Yet, it is worth noticing that placebo group performed the set of tests with slightly better accuracy equal to 2.1%. This should be related to subjects getting familiar and getting used to performing the tests. Rising air temperature revoked this effect and despite performing the same tests 4 times during the experiment, subjects performed it with 0.1% lower productivity.

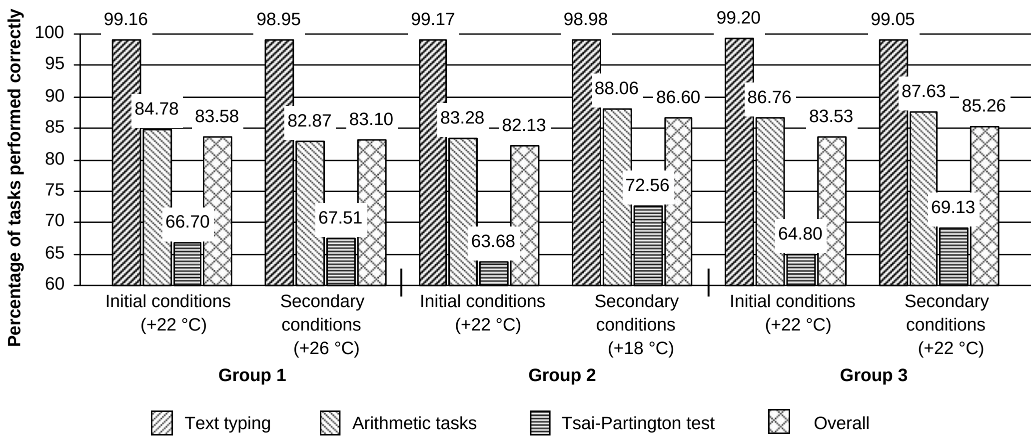

Fig. 4. Work performance expressed from the accuracy of the tests performed by all three groups of subjects

Conclusions

1. In case of the stable air temperature in the room, equal to +22 °C, overall work performance in the second part of the experiment improved by 2.1%. The rise of the temperature from +22 °C to +26 °C triggered the decrement of overall productivity by 0,1% and in case of the temperature drop from +22 °C to +18 °C, overall productivity increased by 5.4%.

2. Participants' subjective assessment showed that the sense of comfort decreased by 7.7% while temperature dropped from +22 °C to +18 °C and in the steady temperature group – by 11.8%. In the group were temperature was raised from +22 °C to +26 °C the sense of comfort decreased by 21.4%. Concentration and efficiency was also mostly affected by the temperature rise to +26 °C.

3. Air temperature change from +22 °C to +18 °C and from +22 °C to +26 °C as well as stable temperature +22 °C has almost no effect (±0.1%) on performance of the text typing tasks, considering mistakes done while typing.

4. Results of the study showed that performance of Tsai-Partington test was influenced most by air temperature change. However, the placebo group performed the test 6.3% better at the second part of the experiment. This indicates that there is a learning trend in performing this test. In the conditions of air temperature drop from +22 °C to +18 °C subjects were more concentrated and performed the Tsai-Partington test with 13.9% higher accuracy. Further experiments could reveal if this effect may be temporal.

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References

Haneda, M.; Tanabe, S.; Nishihara, N.; Nakamura, S. 2008. The combined effects of thermal environment and ventilation rate on productivity, in *Proceedings of the 11th International Conference on Indoor Air Quality and Climate – Indoor Air 2008*, Copenhagen, paper ID: 108.

HN 69:2003. Šiluminis komfortas ir pakankama šiluminė aplinka darbo patalpose. Parametrų norminės vertės ir matavimo reikalavimai, *Valstybės žinios* 45–1485.

EN ISO 7730:2005. Ergonomics of the thermal environment e analytical determination and interpretation of thermal comfort using calculation of the PMV and PPD indices and local thermal comfort criteria. Genève: International Organisation for Standardisation. 2005.

Djukanovic, R.; Wargocki, R.; Fanger, P. 2002. Cost-benefit analysis of improved air quality in an office buildings, in *Proceedings of the 9th International Conference on Indoor Air Quality and Climate – Indoor Air 2002*, Monterey, 808–813.

Fisk, W. J. 2000. Health and productivity gains from better indoor environment ant their relationship with building energy efficiency, *Annual Review of the Energy and the Environment* 25: 537–566. http://dx.doi.org/10.1146/annurev.energy.25.1.537

Fisk, W. J.; Brunner, G.; Doug, B. 2011. Benefits and cost of increasing ventilation rates in U.S. offices, in *Proceedings of the 12th International Conference on Indoor Air Quality and Climate – Indoor Air 2011*, Austin, paper ID: 219.

Fisk, W. J.; Seppänen, O.; Faulkner, D.; Huang, J. 2003. Cost benefit analysis of ventilation control strategies in an office building, in *Proceedings of Healthy Buildings 2003 Conference*, Singapore 3: 361–366.

Hansen, S. O. 1997. Economical consequences of poor indoor air quality and its relation to the total building operation costs, in *EuroFM/IFMA Conference & Exhibition*, June 1997, Torino, Italy.

Kempinski, D. V. 2003. Air and well-being – a way to more profitability. in *Proceedings of Healthy Buildings 2003 Conference*, Singapore, 3: 348–354.

Kosonen, R.; Tan, F. 2004. Assessment of productivity loss in air-conditioned buildings using PMV index, *Energy and Buildings* 36: 987–993. http://dx.doi.org/10.1016/j.enbuild.2004.06.021

Rimkus, E.; Bukantis, A.; Stankūnavičius, G. 2006. Klimato kaita faktai ir prognozes, *Geologijos akiračiai* [Geological horizons] 1(61): 10–20.

Rimkus, E.; Kažys, J.; Junevičiūtė, J.; Stonevičius, E. 2007. Lietuvos klimato pokyčių XXI amžiuje prognozė, *Geografija* [Geography] 43(2): 56–64.

Seppänen, O.; Vuolle, M. 2000. Bost effectiveness of some remedial measures to control summer time temperatures in an office building, in *Proceedings of Healthy Buildings 2000 Conference*, Espoo, 1: 665–660.

Seppänen, O.; Fisk, W. J.; Lei, Q. H. 2006. Room temperature and productivity in office work, in *Proceedings of Healthy Buildings Congress 2006*. 1: 243–247, LBNL-60952.

Šeduikyte, L.; Paukštys, V. 2008. Evaluation of indoor environment conditions in office located in buildings with large glazed areas, *Journal of Civil Engineering and Management* 14(1): 39–44. http://dx.doi.org/10.3846/1392-3730.2008.14.39-44

Tanabe, S. 2005. Productivity and indoor climate, in *Proceedings of the 10th International Conference on Indoor Air Quality and Climate – Indoor Air 2005*, Beijing, 56–64.

Valančius, K.; Skrinska, A. K.; Paulauskaitė, S. 2006. Investigation of unsteady heat transfer process in an once-cell building, *Journal of Civil Engineering and Management*, 12(1): 97–101.

Wargocki, P. 2003. Estimate of economic benefits from investment in improved indoor air quality in office building, in *Proceedings of Healthy Buildings 2003 Conference*, Singapore, 3: 383–387.

Wargocki, P.; Seppänen, O. 2006. Indoor climate and productivity in offices, *REHVA guidebook No.6*. REHVA.

Wargocki, P.; Wyon, D. P.; Matysiak, B; Irgens, S. 2005. The effects of classroom air temperature and outdoor air supply rate on the performance of school work by children, in *Proceedings of 10th International Conference on Indoor Air Quality and Climate – Indoor Air 2005*, Beijing, 368–372.

Wyon, D. P.; Andersen, I.; Lundqvist, G. R. 1979. The effects of moderate heat stress on mental performance, *Scandinavian Journal of Work, Environment and Health* 5: 352–361. http://dx.doi.org/10.5271/sjweh.2646

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