How does low relative humidity affect perceived air quality, thermal comfort and symptoms in modern office buildings in cold climates?

Merethe Lind[1], Sverre Holøs[2*][0000-0003-1405-8724], Kari Thunshelle[2], Aileen Yang[1][0000-0001-7686-9309], Mads Mysen[1,2][0000-0002-5193-2655]

[1]OsloMet – Oslo Metropolitan University (formerly Oslo and Akershus University College of Applied Sciences), P.O Box 4 St. Olavs plass, 0130 Oslo, Norway

[2] SINTEF Building and Infrastructure, Forskningsveien 3B, 0373 Oslo, Norway

Sverreb.holos@sintef.no

Abstract

To assess how people are influenced by relative humidity (RH) in cold climates, a study was conducted in an open office landscape in Oslo, Norway. The study took place during three cold days in February 2017. Fourteen subjects were blindly exposed to different levels of RH in the order of low (14±1%), high (38±3%), and medium (24±4%). The subjects received emails twice a day (at 12:00 and at 14:30) with a link to a webpage where they were asked to: 1) assess perceived air quality (PAQ), 2) respond to a questionnaire about indoor environment quality and symptoms. The subjects performed normal office activity in between the two sessions. We found no significant impact of the level of RH on PAQ. Nevertheless, there were significantly more complaints about dry air at low RH than at medium and high RH. Furthermore, the air was perceived to be significantly more stuffy and heavier at high RH than at medium RH. There were no significant differences in thermal comfort at different RH, yet more people complained that it was cold on the day with low RH and warm on the day with high RH. Generally, there were few complaints related to symptoms at different RH. There were however significantly more complaints of itching and burning in the eyes at low RH than at medium and high RH.

Keywords: Relative Humidity, Perceived air quality, Thermal comfort, Dry air, Symptoms

1 Introduction

Relative humidity (RH) can be as low as 10% during cold and dry winters in Nordic climates, and complaints about dry air happen frequently, especially in office buildings. Studies have shown associations between low humidity and discomfort in the eye, skin and nose of occupants [1]. Furthermore, low humidity could have an impact on respiratory health effects, and thus the Norwegian Institute of Public Health recommends a relative humidity above 20 %[2]. However, humidification of air is generally discouraged due to (I) risk of condensation in the building envelop or on windows, (II) risk of *Legionella* and other microbial growth in humidification systems and (III) high energy and maintenance costs for humidification system [1]. With the current trends toward better insulating windows, low-emitting materials and more air-tight building envelops as well as more advanced demand-controlled ventilation systems, it is conceivable that strategies for avoiding very low humidity without significant trade-offs can be designed. Even without dedicated humidification, reduced ventilation in the coldest period of the year could increase the minimum RH. The goal of this study was to investigate the relation of low relative humidity with performance, perceived air quality (PAQ), thermal comfort and symptoms in a group of office workers in a newly built office building with passive house standard and demand-controlled ventilation.

2 Methods

2.1 Study design

To assess how people are influenced by relative humidity (RH), an intervention study was conducted in an open-plan office in Oslo, Norway. The office is situated in a BREEAM "Very good" certified office building from 2012, with a heated floor area of 14 300 m², and measured airtightness of 0.23 air change rate at 50 Pa. The office has balanced demand-controlled ventilation with infrared and temperature sensors. Furthermore, it is equipped with steam humidifiers (Condair plc, UK), which inject steam to the local supply air to achieve different levels of humidity. Each steam humidifier incorporates a touch screen system to control the humidity level. The study took place during three consecutive cold days in February 2017 with a stable average outdoor temperature of -5 °C. Fourteen subjects (seven females), who were the employees of the companies in the office building, participated in the study. We aimed to blindly expose the subjects to three levels of relative air humidity in the order of low (15±5%), high (35±5%), and medium (25±5%). Indoor temperature, relative humidity and CO_2 concentration were measured and collected using a Rotronic CP 11 (Rotronic AG, Bassersdorf, Switzerland) with a declared accuracy of ±2.5%RH, and a Q-trak 7565-X (TSI Incorporated, Minneapolis, USA). The Norwegian Meteorological Institute provided data on outdoor temperature.

The subjects received emails twice a day (at 12:00 and at 14:30) with a link to a webpage where they were asked to: 1) assess PAQ, 2) respond to a questionnaire about indoor environment quality and symptoms. The schedule was made to maximize attendance, with the test at noon representing a situation short after entry to the room, and 14:30 representing the situation after 2.5 hours of exposure. The subjects performed normal office work in between the two sessions.

2.2 Perceived air quality (PAQ)

PAQ was evaluated using a continuous acceptability scale divided in two parts [3]. The PAQ-acceptability scale was coded as following: 1 = “Clearly unacceptable”, 5 =”Just unacceptable/Just acceptable” and 10= “Clearly acceptable”. It was not possible to score at the midpoint (see Fig. 1).

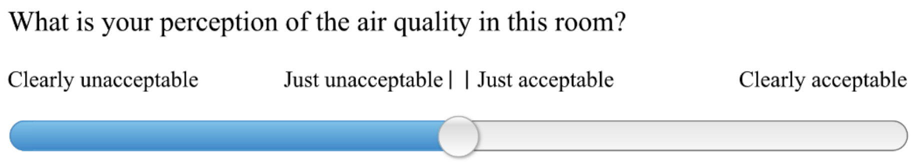

Fig. 1. Assessment of perceived air quality (PAQ). The acceptability score 0 corresponds to "Clearly unacceptable", 5= "Just unacceptable/Just acceptable" and 10 = "Clearly acceptable".

2.3 Questionnaire

The online questionnaire is based on the MM-questionnaire developed at the Department of Occupational and Environmental Medicine in Örebro, Sweden [4], modified to record current intensity on a continuous scale rather than frequency in a recall period.

The questionnaire consists of 25 questions related to subjective assessment of general perceptions of the indoor environment, thermal comfort and sick building syndrome (SBS) symptoms. The questionnaire also included questions on gender, allergy/asthma and location of the work space. A continuous scale slider was used to record the responses to the questions, where the response "No, not at all" was converted to a score of 0 and "Yes, very" to a score of 10. It was not possible to score at the midpoint. Fig. 2 shows an excerpt of the online questionnaire.

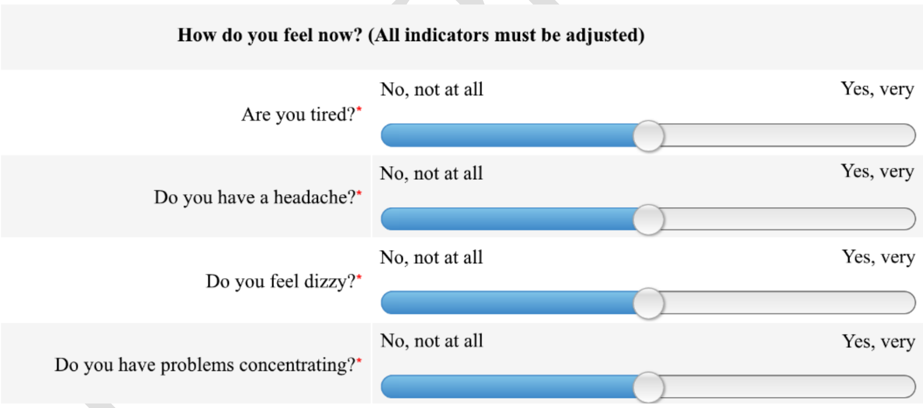

Fig. 2. Excerpt of the online questionnaire. The score 0 corresponds to "No, not at all" and 10 corresponds to "Yes, very".

2.4 Operation span task (OSPAN)

The test Operation span task (OSPAN) was developed by Turner and Engle [5] and is used to determine people's work memory or span of attention. The task consists of deciding whether a mathematical equation is true/false, followed by a four-letter word that needs to be memorized. The test consisted of 12 rounds in random order, with three to seven words per round to memorize. The number of correctly recalled words in the correct order for all 12 rounds, which gives a total of 54 words, was measured.

2.5 Statistical analysis

The responses of the questionnaire were automatically converted into scores where the value 0 corresponds to “No, not at all” and 10 corresponds to “Yes, very”. The PAQ-score was coded as following: 10 = “Clearly acceptable” and 0 = “Clearly unacceptable”.

The non-parametric test Friedman’s ANOVA by ranks was used to check for differences in the responses to the questionnaires (PAQ and indoor climate factors) between the three RH-levels. Whenever significant differences were found, paired comparisons were done with Sign test. OSPAN was analysed using repeated-measures ANOVA. Statistical analysis were performed with SPSS version 24 (SPSS Inc, Chicago, USA).

3 Results

As seen in Table 1, the measured RH levels were well within the intended levels for the three experimental days. The indoor temperature was stable during all three days. The CO_2 concentrations were somewhat higher on the day with low RH, whereas the outdoor airflow rate was higher on the day with medium RH.

Table 1. Average (standard deviation) and [min, max] values of the actual measurement data of relative humidity (RH), indoor and outdoor temperature, outdoor airflow rate ($\dot{V}_{supply}$), and CO_2 concentrations during the experimental days at low, medium and high RH.

RH	Actual RH (%)	T_{indoor} (°C)	T_{out} (°C)	CO_2 (ppm)	$\dot{V}_{supply}$ (m^3/h)
Low	14 (0.2)	22.7 (0.2)	-6.6 (0.2)	696 (33)	363 (31)
	[13, 14]	[22.2, 22.9]	[-6.8, -6.4]	[588, 729]	[301, 424]
Medium	24 (2.5)	22.6 (0.1)	-4.3 (0.2)	627 (28)	444 (66)
	[20, 28]	[22.4, 22.8]	[-4.6, -4.0]	[552, 662]	[355, 612]
High	38 (1.5)	22.7 (0.1)	-5.7 (0.2)	614 (30)	377 (25)
	[35, 41]	[22.6, 22.9]	[-5.9, -5.4]	[528, 653]	[342, 444]

3.1 PAQ

Fig. 3 shows the variations of the PAQ-scores at different RH-levels. A decrease in the score as well as a broader range in individual scores as the relative humidity increases is apparent. However, this decrease in PAQ-score was not statistically significant. Nevertheless, this could indicate that the subjects perceived the air quality to be less acceptable as the relative humidity increased.

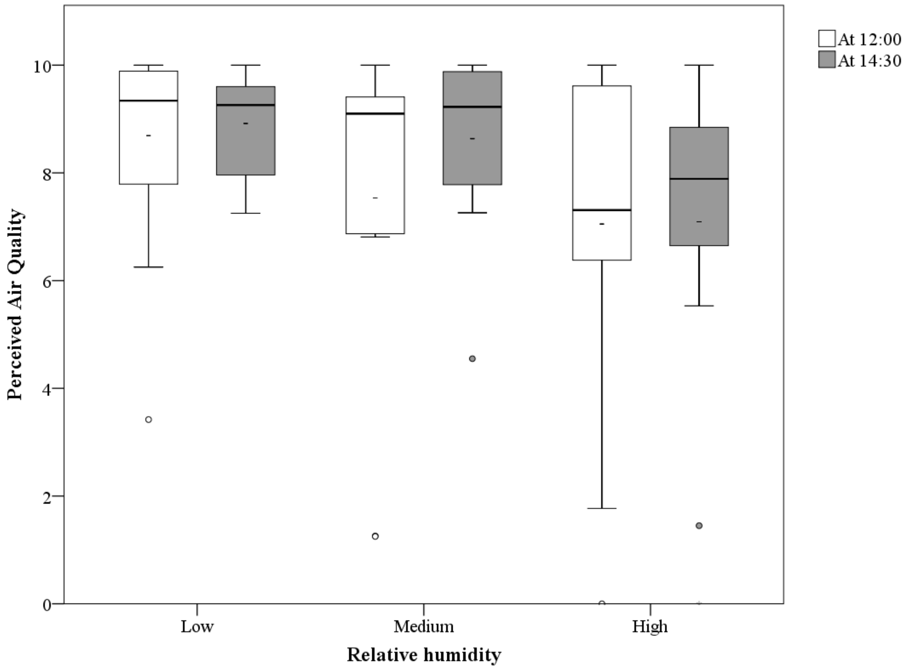

Fig. 3. Boxplot of the PAQ acceptability scores (0 = "Clearly unacceptable", 10 = "Clearly acceptable") by RH-level and session. The dark line in the middle of the boxes is the median, the short line is mean. The top and bottom of the box are the 75th and 25th percentiles. Whiskers indicate the 10th and 90th percentiles and individual outliers are shown as points.

3.2 Questionnaire

Indoor climate factors

The responses to the questions related to indoor climate factors are summarized in Table 2. The median score was 0 for majority of the questions, indicating that the majority of the subjects found the indoor climate generally to be comfortable at all three experimental conditions. The level of RH had a statistically significant impact on sensation of dry air and stuffy air (Friedman's ANOVA, $p<0.05$). The score for dry air was significantly higher at low RH than at medium and high RH (Sign Test, $p<0.01$) at 12:00, but not at 14:30.

The score for the question related to stuffy air increased with increasing RH. Interestingly, the score for stuffy air was only significantly higher at high RH compared with medium RH (Sign Test, $p<0.05$).

Although no impact of RH was found on factors related to thermal comfort, there were indications of more subjective complaints that it was cold on the day with low RH (mean score of 2.53) and warm on the day with high RH (mean score of 3.32).

Table 2. Mean and median values of the responses to the questionnaire related to indoor climate factors at low, medium and high RH at 12:00 and at 14:30.

	At 12:00 (Mean/median)			**At 14:30 (Mean/median)**		
	Low N=14	**Medium N=12**	**High N=12**	**Low N=14**	**Medium N=12**	**High N=12**
Dry air*	1.67/0.23	0.09/0	0.06/0	1.95/0.27	1.71/0	0.02/0
Stuffy air*	0.71/0	0.96/0	3.48/1.55	0.43/0	1.33/0	3.22/0.79
Unpleasant odor	0.07/0	1.40/0	1.43/0	0/0	1.72/0	2.34/0
Too cold	2.53/0	1.24/0	1.4/0	2.65/0.73	1.55/0	1.29/0
Too warm	0.34/0	0.61/0	3.32/2.12	0.56/0.08	0.94/0	1.47/0.03
Draught	1.54/0	0.64/0	0.07/0	1.86/0	1.44/0	0.17/0
Varying temperature	1.77/0	1.44/0	2.08/0	1.33/0	1.28/0	1.83/0
Heat from sun	0.18/0	0/0	0/0	0.11/0	0/0	0/0

*$p<0.05$, Friedman's ANOVA

SBS symptoms

The responses to the questions related to SBS symptoms are summarized in Table 3. Overall, there were few complaints related to symptoms at different RH-levels as the median score for majority of these questions were 0. The average symptom intensity was highest at low RH for all symptoms except difficulties concentrating and nausea at 14:30. The score for itching and burning of the eyes was significantly higher at low RH compared with medium (Sign test, $p<0.01$) and high RH (Sign test, $p<0.05$) in the afternoon. The score for fatigue was significantly higher (Sign test, $p<0.05$) at low RH than at medium RH, both at noon and at 14:30.

Table 3. Mean and median values of the responses to the questionnaire related to SBS symptoms at low, medium and high RH at 12:00 and at 14:30.

	At 12:00 (Mean/median)			**At 14:30 (Mean/Median)**		
Symptoms	**Low N=14**	**Medium N=12**	**High N=12**	**Low N=14**	**Medium N=12**	**High N=12**
Fatigue	2.84/2.30	1.21/0.63	2.73/1.26	3.72/3.77	2.00/0.84	2.77/1.7
Heavy-headed	2.20/1.05	0.46/0	1.60/0.24	2.55/2.42	1.62/0.3	2.52/1.46
Headache	0.63/0	0.03/0	0.10/0	0.11/0	0.83/0	0.87/0
Dizziness	1.18/0	0.64/0	0.25/0	1.26/0	0.89/0	1.05/0
Difficulties concentrating	2.93/1.60	1.96/0.27	2.66/1.32	2.16/1.17	3.26/1.52	3.42/2.45
Itching, burning eye*	1.63/0	0.01/0	0.19/0	1.75/0.32	0.11/0	0.35/0
Hoarse,dry throat	0.87/0	0.02/0	0.11/0	1.18/0	0.12/0	0.63/0
Itching hands/face	1.14/0	0.10/0	0.07/0	0.62/0	0.35/0	0.07/0
Nausea, unwellness	0.63/0	0.46/0	0.55/0	0.64/0	1.39/0	1.14/0

*$p<0.05$, Friedman's ANOVA

3.3 OSPAN

The results of the OSPAN test varied widely between individuals as illustrated in Fig. 4. Only nine subjects completed the test for all three days. The total number of accurate words in correct order is 54 per test round. We did not find any significant effect of RH-level on the cognitive performance of the subjects.

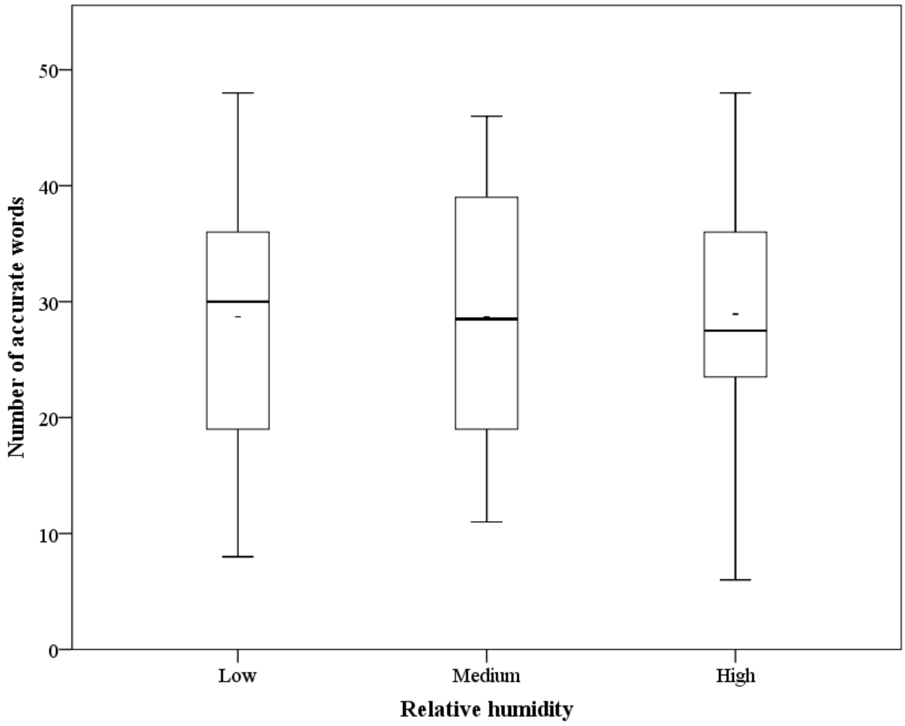

Fig. 4. Number of accurate words in correct order (total N= 54 words) by RH-level. The dark line in the middle of the box is the median, the short line is the mean. The top and bottom of the box are the 75th and 25th percentiles. Whiskers indicate the 10th and 90th percentiles and individual outliers are shown as points.

4 Discussion

The aim of this study is to assess the impact of RH level on PAQ, indoor climate factors related to human comfort and cognitive performance, in a humidity range relevant for office buildings in Nordic winter situations. The lowest level of 14% corresponded to normal operation of the study building at an outdoor temperature of -5ºC. In such a weather situation, 38% RH was considered representative for the highest relevant humidity for an office building.

A recent review by Derby et al. [1] identified several studies on the effect of low humidity on comfort, health and indoor environmental quality (IEQ). They noted that perceived quality or acceptability of air generally decreases with increasing temperature and RH. Oftentimes, also on the odor intensity, which is related to the concentrations of volatile organic compounds (VOCs). In order to disentangle the effect of temperature from the effect of RH, we kept the temperature constant during the three experimental days.

In our study, we found no statistically significant impact of RH on the PAQ-score as assessed according to the method by Gunnarsen and Fanger [6], although PAQ-score did decrease with increasing humidity. Also, the scores for stuffy air and unpleasant odor showed an increasing tendency with increasing RH. This is in line with previous observations in several studies that increasing enthalpy decreases acceptability of the air and individual air quality indicators with RH in the range 20% - 70% [3,7–9]. Possible causes for such a relationship include increased olfactory sensitivity or increased emissions from pollution sources at higher enthalpy, or perhaps a satisfying experience resulting from the cooling of the airways at lower enthalpy. The humidification process could also lead to increased pollution of the air if the water or equipment is not free from pollutants. In our experimental setup, we have no way of assessing the relative contribution of different causes.

Wyon et al. [10] observed no effects of humidity on PAQ when thirty subjects were exposed for 5h to clean air at 5%, 15%, 25% and 35% RH at 22 °C. Unlike our study, the exposure to RH were done in experimental chambers [10]. It would be of interest to repeat the study by Wyon et al. [10] in an actual work situation with more subjects, in order to examine if the results are representative for newer office buildings.

Previous studies have reported the perception of dry air to be poorly correlated with humidity [1,7]. The literature is inconclusive on whether participating subjects are able to perceive low humidity, albeit studies have shown that people prefer rather dry and cool air and decreased humidity (down to 20% RH) has a beneficial effect on PAQ [7,11].The sensation of dry air increases with increased temperature and air velocity. The most probable cause of sensation of dry air could be elevated levels of pollutants such as particulate matter and dust [11]. In contrast, our results indicate that the subject are able to perceive dry air as they found the air to be too dry at 14% RH compared to an RH level above 24%. We measured similar outdoor airflow rates during the three experimental days, and the indoor temperatures were very similar. Even if particulate pollutants were not measured, it is reasonable to assume a constant and low level of particulate concentrations in the supply air for all three days.

Derby et al.[1] also reported an increase in skin dryness, eye irritation as the humidity decreased in a review of several studies. Generally, these studies indicate a breakpoint between 20-30% RH for discomfort to skin, eyes and membrane irritation [1,12]. Our findings are in line with these previous results, as fewer subjects complained of itchy and burning eyes at 24% and 38% RH.

Theoretically, the thermal balance of a person is affected by the enthalpy of the air, meaning that more heat is lost to dry than moist air at the same temperature due to evaporative heat loss. The subjects reported being too cold at low RF, and too warm at high RF. However, thermal sensation is highly affected by clothing and activity level, and the study design did not control for this.

Overall, our results indicate that RH-levels at 14-24% may reduce comfort in a well-ventilated building with low-emitting materials, while it is less obvious that increasing RH to 24-38% increases comfort. Given the inherent weakness in study design where interventions are examined sequentially on different days with a limited number of subjects, these indications obviously need confirmation with a larger study population before they are used in designing strategies for building operation. However, our results support previous findings that even relatively small increases in RH from the very low levels commonly observed in well-ventilated office buildings at below-zero outdoor temperatures may have beneficial effects. Thus, further examination on possible measures for increasing indoor RH without negative effects is called for.

5 Conclusion

We found no significant impact of level of relative humidity on PAQ and cognitive performance. However, we found more complaints of dry air at 14% RH compared with an RH level above 24%. Furthermore, more subjects complained about itchy and burning eyes at 14% RH. Our study indicates that increasing relative humidity can reduce complaints and symptoms due to dry air. However, increased complaints of stuffy air were observed at 38% RH.

6 Acknowledgements

We would like to thank the participants from GK A/S for their assistance and participation in this project. This paper is based on the master thesis by Merethe Lind, and was a part of the BEST VENT project. BEST VENT is funded by the Research Council of Norway EnergiX program under Grant 255375/E20 together with the industry partners: Undervisningsbygg Oslo KF, GK Inneklima AS, DNB Næringseiendom AS, Erichsen & Horgen AS, Hjellnes Consult AS, Multiconsult AS, Interfil AS, Camfil Norge AS, Swegon AS, Belimo Automasjon Norge AS, NEAS AS, and Norsk VVS Energi- og Miljøteknisk Forenings Stiftelse for forskning.

Compliance with ethical standards

Formal consent was given by the volunteers who participated in this study. We did not collect any identifiable or sensitive information that would require ethical approval. The research has been conducted in compliance with the ethical standards at OsloMet – Oslo Metropolitan University (formerly Oslo and Akershus University College of Applied Science) and Norwegian Law.

References

1. Derby MM, Hamehkasi M, Eckels S, Hwang GM, Jones B, Maghirang R, et al. Update of the scientific evidence for specifying lower limit relative humidity levels for comfort, health, and indoor environmental quality in occupied spaces (RP-1630). Sci Technol Built Environ 2017;23:30–45. doi:10.1080/23744731.2016.1206430.
2. Folkehelseinstitutt. Anbefalte faglige normer for inneklima. Revisjon av kunnskapsgrunnlag og normer – 2015. Oslo, Norway: Folkehelseinstituttet; 2015.
3. Fang L, Clausen G, Fanger PO. Impact of Temperature and Humidity on the Perception of Indoor Air Quality. Indoor Air 1998;8:80–90. doi:10.1111/j.1600-0668.1998.t01-2-00003.x.
4. Andersson K. Epidemiological Approach to Indoor Air Problems*. Indoor Air 1998;8:32–9. doi:10.1111/j.1600-0668.1998.tb00005.x.
5. Turner ML, Engle RW. Is working memory capacity task dependent? J Mem Lang 1989;28:127–54. doi:10.1016/0749-596X(89)90040-5.
6. Gunnarsen L, Fanger PO. Adaptation to indoor air pollution. Environ Int 1992;18:43–54. doi:10.1016/0160-4120(92)90209-M.
7. Fang L, Wyon DP, Clausen G, Fanger PO. Impact of indoor air temperature and humidity in an office on perceived air quality, SBS symptoms and performance. Indoor Air 2004;14:74–81. doi:10.1111/j.1600-0668.2004.00276.x.
8. Fang L, Clausen G, Fanger PO. Impact of Temperature and Humidity on Chemical and Sensory Emissions from Building Materials. Indoor Air 1999;9:193–201. doi:10.1111/j.1600-0668.1999.t01-1-00006.x.
9. Reinikainen LM, Aunela-Tapola L, Jaakkola JJ. Humidification and perceived indoor air quality in the office environment. Occup Environ Med 1997;54:322–7.
10. Wyon DP, Fang L, Lagercrantz L, Fanger PO. Experimental Determination of the Limiting Criteria for Human Exposure to Low Winter Humidity Indoors (RP-1160). HVACR Res 2006;12:201–13. doi:10.1080/10789669.2006.10391175.
11. Ole Fanger P. What is IAQ? Indoor Air 2006;16:328–34. doi:10.1111/j.1600-0668.2006.00437.x.
12. Wolkoff P, Nøjgaard JK, Franck C, Skov P. The modern office environment desiccates the eyes? Indoor Air 2006;16:258–65. doi:10.1111/j.1600-0668.2006.00429.x.