Proceedings of 8th Windsor Conference: ***Counting the Cost of Comfort in a changing world*** Cumberland Lodge, Windsor, UK, 10-13 April 2014. London: Network for Comfort and Energy Use in Buildings, http://nceub.org.uk

Robust Design for high workers' performance and low absenteeism – An alternative approach

Joe L. Leyten [1], Arjen K. Raue [2], Stanley R. Kurvers [3]

[1] Utrecht, The Netherlands, mailto: joeleijten@planet.nl
[2] Utrecht University, The Netherlands
[3] Delft University of Technology, Faculty of Architecture, Delft, The Netherlands

Abstract

Rehva Guide No 6 – Indoor Climate and Productivity in Offices - states as its main purpose to establish quantitative relationships of indoor environmental aspects with performance and sickness absenteeism. The following relationships were established: temperature with performance, ventilation with performance, perceived indoor air quality with performance and ventilation with sickness absenteeism. The purpose of this paper is to establish what in practice are, or probably are, the most effective measures to increase performance and decrease absenteeism, given the total of the presently available evidence. We argue that robust measures, like avoidance of indoor air pollution sources, minimizing external and internal heat load, thermal effective building mass, cellular office layout with shallow plan depth, occupant control of temperature, operable windows and providing for adaptive thermal comfort are more effective in increasing performance and reducing absenteeism than less robust measures like diluting indoor air pollution through increased ventilation, controlling temperature through mechanical cooling and open plan workroom layout combined with deep plan depth.
.

Keywords: Workers' performance, sickness absenteeism, adaptive thermal comfort, indoor air quality, building robustness.

1 Introduction

In 2006 the Federation of European Heating and Air-conditioning Associations Rehva published Rehva Guide No 6 – Indoor Climate and Productivity in Offices – How to integrate productivity in life-cycle cost analysis of building services (from hereon: the Rehva Guide). The Rehva Guide states as its main purpose to establish quantitative relationships of indoor environmental aspects with performance and sickness absenteeism. The following relationships were established: temperature with performance, ventilation with performance, perceived indoor air quality with performance and ventilation with sickness absenteeism. The purpose of this paper is to establish what in practice are, or probably are, the most effective measures to increase performance and decrease absenteeism, given the total of the presently available evidence.

2 Temperature and performance

The impact of temperature and thermal sensation on building occupant performance has been reviewed extensively in Leyten, Kurvers and Raue (2012). The most important results are:

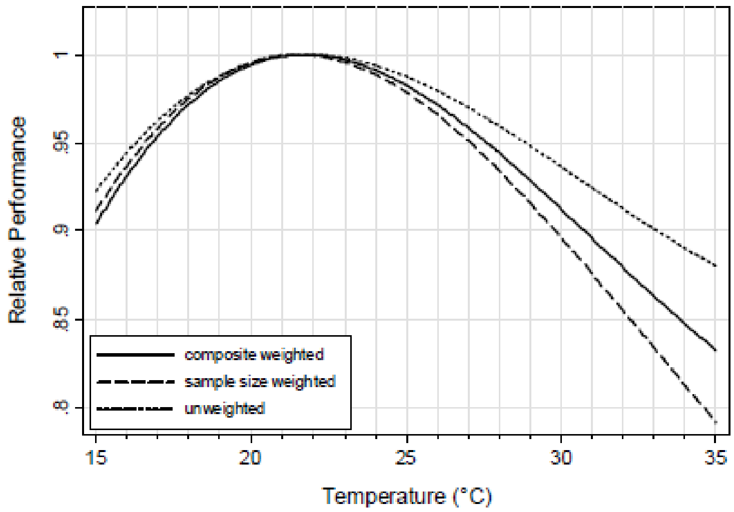

Figure 1. Relative performance vs. temperature according to Rehva Guideline No 6. Maximum performance is set equal to 1. Source: Seppänen et al. (2006a).

- The Rehva Guide presents a relation of performance with temperature based on a meta-analysis of 24 studies concerning objectively measured performance. Figure 1 shows the results of the meta-analysis. According to the figure performance is maximal at 21.75˚C. Above and below this temperature performance decreases. The Rehva Guide states that the effect shown in figure 1 is statistically significant only below 20˚C and above 24˚C, so the temperature range of maximal performance roughly coincides with the comfort temperature for air-conditioned environments. However, none of the 24 studies concerns a free running naturally ventilated (from hereon: free running) office environment. In almost all of these studies the major mechanisms by which occupants in free running environments accept higher temperatures and feel neutral at higher temperatures in warmer climates and during the summer period in moderate climates, are prevented from working or strongly impeded. Therefore the relationship presented in the Rehva Guide cannot be extrapolated to free running environments.
- In free running environments we expect maximal performance at the matching comfort temperature, which can be considerably higher than 21.75˚C.
- When it comes to comparing air conditioned environments at the matching comfort temperature and free funning environments at the matching comfort temperature, we expect performance to be higher in free running environments because therein occupant satisfaction with the indoor environment will be higher and Building Related Symptoms (from hereon: BRS), including fatigue, headache and problems concentrating, will be less.

3 Ventilation rate and performance

The Rehva Guide gives a relation between ventilation rate and performance based on five field studies in offices and two laboratory studies. The results are shown in figure 2 with 6,5 l/s*person and 10 l/s*person as reference values. If the curves weighted by sample size and outcome relevance are selected performance increases 1% when ventilation rate is increased from 6.5 to 10 l/s*person and increases another 1% when ventilation rate is increased from 10 to 17 l/s*person. Seppänen et al. (2006b) states that performance increases statistically significantly in the ventilation range of 6.5 to 17 l/s*p with 90% confidence interval (from hereon: CI) and up to 15 l/s*p with 95%

CI. Even if we leniently choose the 90% CI, there is no statistically significant effect above 17 l/s*p, which implies that the maximum performance gain that can be reached by increasing the ventilation rate above 10 l/s*p is 1%.

4 Alternatives to increasing ventilation rate

The Rehva Guide also includes results of studies into the effect of different indoor air pollution sources on performance:

- Removal of used soiled carpet: 6.5% performance gain.
- Removal of relatively new CRT monitors: 9% performance gain.
- Replacing used air intake filters for new ones: 10% performance gain.

The Rehva Guide gives two relations of performance with percentage dissatisfied with air quality, respectively 0.8% and 1.1% performance gain for each 10% less dissatisfied with indoor air quality. Since these relations are based on slightly different, partly overlapping data, we propose a simplified relation of 1% performance gain for each 10% less dissatisfied with indoor air quality. This relation implies additivity of the effect of pollution sources. When it comes to the indoor air pollution caused by building materials Knudsen and Wargocki (2010) show that perceived air quality in workrooms can be improved by replacing a high polluting material by a low polluting material. The effect was most pronounced when the most polluting material was replaced by a less polluting material. This improvement was more pronounced than that achieved by a realistic increase of outdoor supply air. For the high polluting materials it was seen that, even at the highest ventilation rate at $6.4h^{-1}$, it was far from possible to achieve an acceptable level of perceived air quality. The main conclusion of Knudsen and Wargocki (2010) is that the use of low polluting materials reduces the ventilation rate required to achieve an acceptable level of perceived air quality and thereby prevents unnecessary use of energy for ventilation. Improved perceived air quality implies a lower percentage dissatisfied with air quality and thereby higher performance. The effect of the removal of relatively new CRT monitors, although hardly used anymore nowadays, suggests that the emission of other office machines may also reduce performance and that they should either be selected for low emission or placed in separate rooms with dedicated ventilation. Fitzner (2000) shows that pollution source strength from other HVAC components of HVAC systems, e.g. cooling sections, air humidifiers and rotary heat exchangers is comparable with that of air intake filters. Bluyssen et al. (2003) elaborate on how to avoid pollution sources in the HVAC system. All in all it is safe to expect that a strict avoidance of indoor air pollution sources in both HVAC systems and workrooms will result in a performance gain much higher than achievable by increasing ventilation. Given de percentages mentioned above a combined performance gain of 10% or more is expected, when compared to conventional practice.

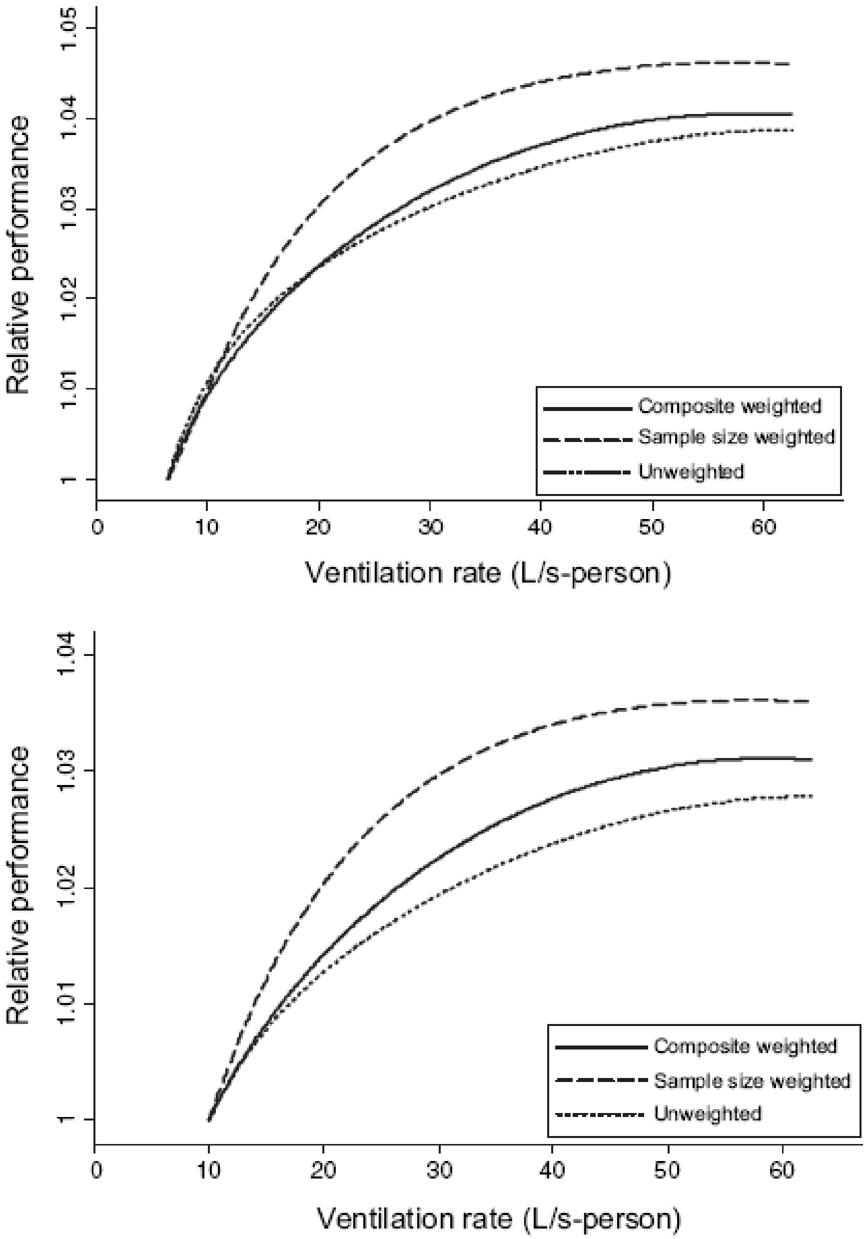

Figure 2. Relative performance in relation to the reference values 6.5 l/s-person (upper) and 10 l/s-person (lower) vs. ventilation rate according to Rehva Guide No 6. The outlier data point is not included. Source: Seppänen et al. (2006b).

Table 1. Prevalence (%) of adverse environmental perceptions and symptoms in various office types. Adapted from Pejtersen et al. (2006).

	Office size (number of occupants per room)				
Perception or symptom	*1*	*2*	*3-6*	*7-28*	*>28*
Too high temperature	11	10	21	23	34
Varying temperature	8	14	17	28	25
Too low temperature	6	10	14	17	17
Stuffy air	21	29	36	42	54
Dry air	19	25	31	39	50
Noise in the room	6	15	28	42	60
Inadequate lighting	9	13	15	20	23
Reflections (glare)	11	13	15	21	26
Fatigue	8	12	12	17	21
Headache	10	14	13	19	25
Difficulties concentrating	2	6	6	8	16

Table 1 shows the most important of the statistically significant results of Pejtersen et al. (2006). Occupant dissatisfaction with, among others, thermal comfort, indoor air quality, noise in the room, lighting and reflections (glare) and BRS, among them fatigue, headache and difficulties in concentrating, all rise with increasing number of occupants per workroom. Similar results were found by Wilson and Hedge (1987), Zweers et al. (1992), Fisk et al. (1993) and Brasche et al. (2001). Therefore it is expected that performance will increase by housing workers in cellular offices instead of in open plan offices.
The effect of thermal discomfort is difficult to quantify as there is no direct relation between the several aspects of discomfort in table 1 and the relations found in the previous paragraph.
The effect of dissatisfaction with indoor air quality can be quantified if we assume that the percentage of workers reporting dry air[1] is a good proxy for the percentage dissatisfied with indoor air quality. If we take two occupants per workroom as reference level, the effect of indoor air quality varies from 0.6% performance loss for 3 to 6 occupants per workroom to 2.5% for more than 28 occupants per room.
The effect of dissatisfaction with noise in the room cannot be deduced from table 1 directly, but Hongisto (2005) gives a relation of performance with STI (Speech Transmission Index) based on a large number of studies from which it can be deduced that performance loss caused by noise in the room will vary from 3% in a acoustically well designed open plan office to 7% in a acoustically poorly designed open plan office (figure 3).

[1] Perception of dry air is caused by indoor air pollutants rather than by low air humidity

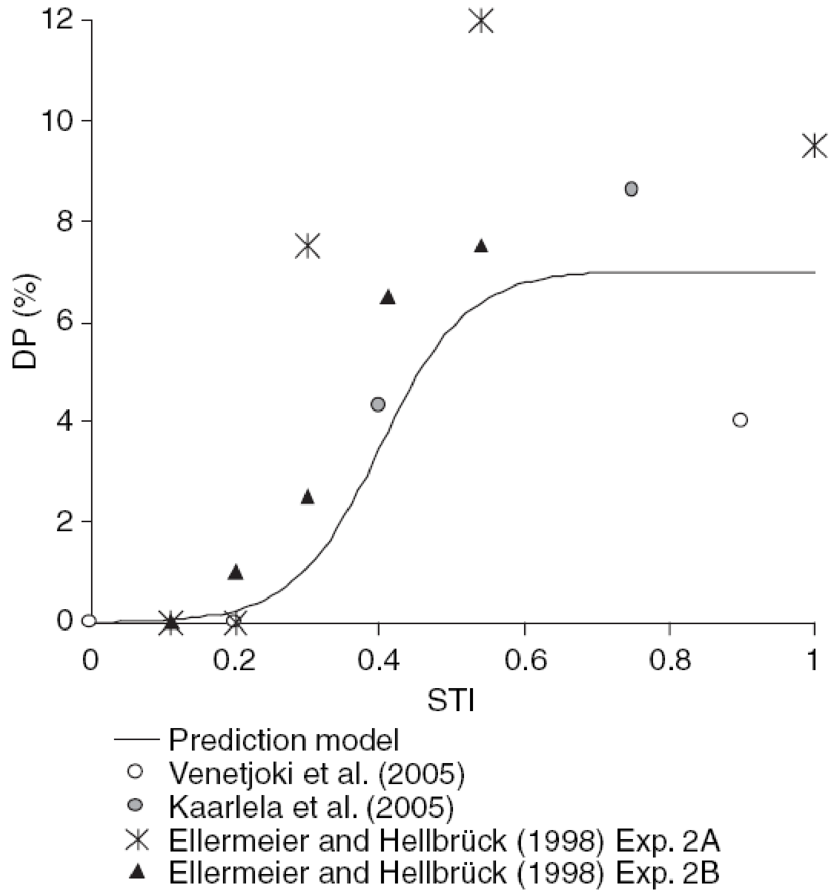

Figure 3: The schematic prediction model, which gives the decrease in performance, DP, as a function of the STI. The highest performance is obtained when no speech is heard (STI ¼ 0.00, conventional office) and the highest performance decrease is reached when speech is highly intelligible (STI > 0.70, poor open-plan office), irrespective of sound level of speech. The normalization constant of Equation 1 was A2 ¼ 7%. Source: Hongisto (2005).

The effects of inadequate lighting and glare cannot be quantified with present knowledge, but some effects are expected. Heschong Mahone Group (2003) found that a higher risk of glare decreased mental test performance by 15% to 21%. They also found that workers in a call-centre were found to process calls 7% to 12% faster when they had the best possible outside view versus those with no view. These figures are possibly an overestimation because of lack of control for confounders: glare and the quality of the view may be proxies for other relevant workplace characteristics. Frontczak et al. (2012) confirm the importance of the view from the workplace: people sitting close to a window expressed significantly higher workplace satisfaction than those further from a window.

The effect of BRS (including fatigue, headache, difficulties concentrating) cannot be quantified with present knowledge. The Rehva Guide lists a number of studies but concludes that a meta-analysis is problematic because of large differences in design and definitions. Two studies measured call-centre performance and simultaneously registered BRS. Both studies show that a reduction of central nervous symptoms (e.g. headaches, difficulty to think clearly) corresponds to improved performance. So the increase of BRS with larger room size is expected to lower performance.

Cellular offices allow for occupant control of temperature in a way that open plan offices do not. Based on a theoretical model, Wyon (2000) predicts a performance gain of 2.7 to 8.6% with an average of 5.4% for various different tasks when occupants can control their thermal environment. To be on the safe side it is assumed that the effect in offices will be 2.7 to 5.4%, which is supported by a 4% gain found in a field study (Kroner & Stark-Martin, 1994).
The Rehva Guide proposes the following rule to add several different performance effects: The magnitude of the combined effects is at least the effect of the greater of the single parameters, and not more than the sum of the independent parameters. When we apply this carefully with some creativity to the effect of housing in open plan offices instead of in cellular, two person offices with occupant control of temperature, the effect is 3 to 14.9% performance loss, possibly plus the unknown effects of dissatisfaction about lighting, glare and view and of BRS and an unknown residual effect of thermal discomfort (it is assumed that the unknown effect of thermal discomfort is already for the most part incorporated in the effect of occupant control of temperature). Actually a minimum effect somewhat higher than 3% is to be expected because Raw et al. (1990) shows that, albeit for self estimated performance, the effects of open plan offices and of lack of occupant control are independent, so some additivity of the two is expected.

The above shows that avoidance of indoor air pollution sources and housing in cellular offices are more effective in increasing performance than increasing ventilation. There is yet another problem with increasing ventilation instead of avoiding indoor air pollution sources. In some situations increased ventilation leads to increased emission of pollutants. Wargocki et al. (2004), a field study, shows that when the ventilation rate is increased in the case of used, polluted filters increased ventilation leads to a decrease of the perceived indoor air quality and of performance. The conclusion is that the increased ventilation leads to higher emission of pollutants from the polluted filters. A similar effect on perceived indoor air quality is found by by Alm, Clausen and Fanger (2000) and by Strøm-Tejsen, Clausen and Toftum (2003), both studies showing that the pollution load from a used filter increases proportionally with the air velocity across the filter. It cannot be excluded that this also applies to other pollution sources within the HVAC system. Another example of increased pollutant emission as a result of increased ventilation is given by Bakó-Biró (2004) The results show that if the indoor air contains pollutants that are sensitive to oxidation, like terpenes, emission of pollutants increases with increased ventilation if the ventilation air contains ozone. These examples show that in various situations, increasing ventilation may lead to higher emission of pollutants. This problem can of course be eliminated by strict avoidance of pollution sources. When this strategy is followed, it is sufficient to apply a low but adequate ventilation level, which can be delivered by simple mechanical ventilation or even by natural ventilation.

5 Ventilation rate, workroom layout and sickness absenteeism

The Rehva Guide presents a quantitative relationship between ventilation rate and short-term sickness absenteeism by combining published data from four field studies and making use of the Wells-Riley equation, plus a theoretical model of airborne transmission of respiratory infections (Fisk et al., 2003). These relations are shown in figure 4. The particle concentration model curve uses a simple model in which the disease prevalence is proportional to the reciprocal of the total infectious particle removal rate. A rough estimate using the presented relationship suggests a 10%

reduction in illness for doubling of outdoor air supply rate. The Rehva Guide states that this relationship is only valid in open plan offices or when the air is recirculated within the office building. This suggests the possibility to reduce absenteeism caused by infectious diseases by avoiding both open plan offices and recirculation.

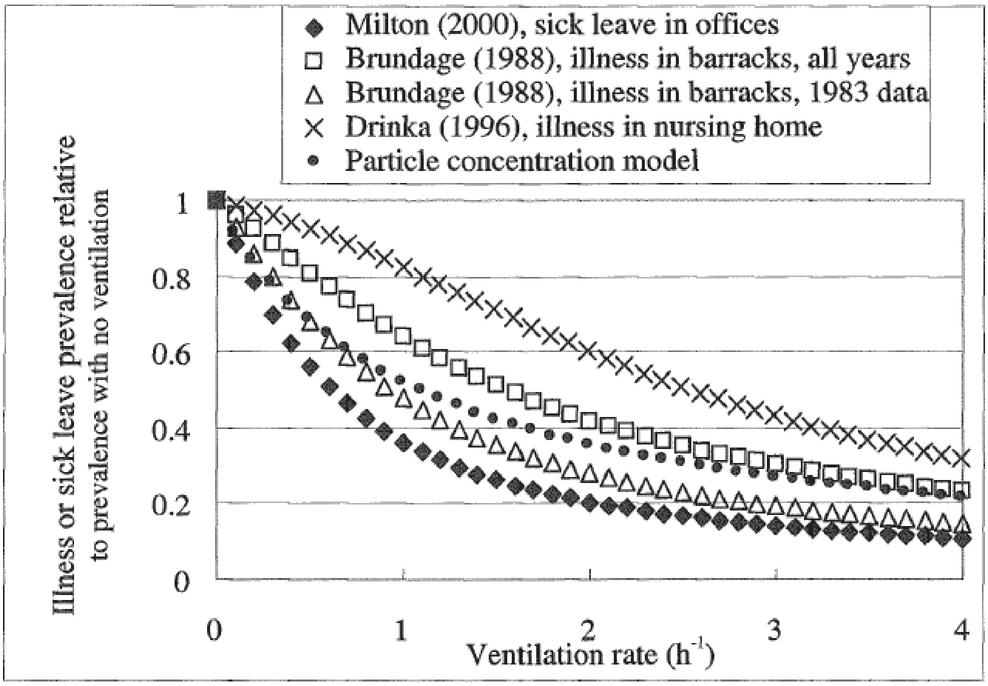

Figure 4: Predicted trends in illness of sick leave versus ventilation rate. Source: Fisk et al. (2003).

At least one study (Jaakkola and Heinonen, 1995) shows that workers working in single rooms have less objectively registered episodes of the common cold than workers who share their work space with others. It is however more interesting to know what the effect would be of housing in two or three person rooms, because that is the most frequent layout in the case of cellular offices, at least in The Netherlands. Furthermore the contacts that workers have visiting other rooms should be accounted for. Thus either we need more empirical data about the relation between office layout and registered absenteeism, or at least a theoretical model to predict the effect of office layout. For the latter we need at least empirical data about the frequency and length of visits to other rooms. All this is beyond the scope of this paper. For the time being the conclusion is that avoiding open plan offices and recirculation is at least an effective alternative to increasing ventilation rate when it come to reducing absenteeism.

6 Indoor air pollution sources and sickness absenteeism

Milton et al. (2000) is one of the few well executed studies based on objectively registered absenteeism. It shows that the effect of the use of a humidifier in the HVAC system on total absenteeism is of approximately the same size as the effect of reducing ventilation rates from 24 to 12 l/s*person. The humidifiers in this study included steam, spray and finfill devices. Milton et al. (2000) gives as a possible explanation of the association of humidification with increased absenteeism that humidification may have promoted increased bioaerosol exposure. More generally it can be stated that using a humidifier increases absenteeism because it can be an indoor air pollution source. Eliminating several or all indoor air pollution sources may be more effective in reducing absenteeism than doubling the ventilation rate.

7 Workers' satisfaction with the indoor environment and sickness absenteeism

Table 3: Annual absenteeism for office workers only. Adapted from Milton et al. (2000).

Area with formally registered Indoor air complaints	Long-term absenteeism (> 10 days)	Short-term absenteeism (≤ 10 days)
No	2.17%	1.60%
Yes	1.30%	1.91%

The results of Milton et al. (2000) also show that the effect of working in an area *with formally registered indoor air complaints* on short-term absenteeism is of approximately the same size as the effect of higher ventilation compared to lower ventilation. Table 3 shows long-term and short-term absenteeism for areas with or without indoor air complaints for office workers only, as found in Milton et al. (2000). Presence of complaints was defined as whether a formal complaint had been made to the corporate environmental health and safety office within the last three years. It was found that working in a complaint area increases only short-term absenteeism. A plausible explanation for this is as follows: Generally there are two paths along which work related burdens can increase absenteeism (Oversloot, 1995):

- The burdens directly cause the illness or the medical complaints, e.g. lifting too heavy loads causes back pain or contact with contaminated blood causes infectious disease.
- The burden does not in itself cause illness but it does cause dissatisfaction with the work environment and diminished loyalty to the organisation. When an employee suffers from a non serious illness (e.g. common cold or headache) he or she is not necessarily incapable of working, but the diminished loyalty will increase the probability that he or she reports ill. Moreover, when the symptoms decrease at the end of the sickness period, the employee has a certain latitude of choice to report well earlier or later, and if possible he or she will postpone reporting well (e.g. from Friday till Monday) if loyalty to the organisation is low. This of course also depends on the legal and cultural tolerance towards reporting ill, which can vary considerably among organisations and countries. Because this mechanism normally only works in the case of non serious illness and its relative effects are greater in the case of short sick leave it leads to an increase of short-term absenteeism rather than of long-term absenteeism.

Published data indicate that indoor air problems increase absenteeism along the two paths described above: On the one hand inadequate ventilation and indoor air pollution increase the probability of infectious illnesses like influenza and the common cold (see the literature reviewed in Milton et al., 2000). On the other hand Robertson et al. (1990) reports that when workers from the same organisation move from a building part with good indoor air quality to a part with poor indoor air quality, the registered absenteeism increases in *all* diagnose categories, and not only in those that are indoor air quality related. Workers who move in the opposite direction show a decrease of absenteeism in *all* diagnose categories. This indicates that poor air quality increases the probability of reporting ill and of postponing reporting well even if the illness itself is not related to indoor air quality. The results from Milton et al. (2000) in table 3 support this view. It turns out that in building parts with a high level of indoor air complaints there is more short-term absenteeism compared to building parts with a low level of complaints which is what would be expected if indoor air complaints would at least partly increase absenteeism *via* decreasing loyalty[2]. A typical situation that decreases loyalty is working in an open plan office. This causes dissatisfaction about many aspects of the indoor environment and BRS (Pejtersen et al. 2006) and lowers both self-estimated (Raw et al., 1990) and objectively measured performance (this paper). Loyalty will be especially reduced when it is a management decision to work in an open plan layout and workers would prefer cellular offices.

8 Self reported absenteeism

The results above are based on objectively registered absenteeism. This allows for stronger conclusions than self reported absenteeism, but there are few studies based on objectively reported absenteeism. It is therefore interesting to see if the above results are supported by data concerning self reported absenteeism. We have decided to include three well executed studies. The first study (Preller et al. 1990a) concerns a large number of workers (7043) and buildings (61), which, apart from self reported absenteeism, includes data about workers' satisfaction with the indoor environment and BRS. Furthermore, a large number of worker, building and workplace characteristics were registered and multivariate analysis was applied. Table 4 shows the relevant results. In this publication both types of humidifiers are associated with an increase of all measures of self reported absenteeism. From Preller et al. (1990a) it is known that the characteristic *mechanical cooling*, which in this study correlates highly with the presence of humidifiers and in the univariate analysis correlates significantly with BRS and dissatisfaction, was not included in the multivariate analysis to avoid collinearity problems. This implies that in this publication the characteristics *spray or steam humidifier* actually stand for the characteristic *humidifier and/or mechanical cooling*, which supports the earlier conclusion that indoor air pollution sources in general increase absenteeism. The characteristic *satisfied with IEQ complaint handling* is a good proxy for the absence of complaints about the indoor environment, since dissatisfaction with complaint handling is only to be expected when there are IEQ problems to complain about. So the relation of this characteristic with a decrease of all self reported absenteeism measures supports the earlier conclusion that general workers' satisfaction with the indoor environment decreases absenteeism. (The presentation of the data does not allow for a conclusion specific to short-term absenteeism). Preller et al. (1990a) find no relation of any of the absenteeism measures with the number of workers per room, in this publication defined as ≥ 10 versus < 10.

The second study (Pejtersen et al., 2011) and the third study (Bodin Danielsson et al, 2014) concern the relation of self reported absenteeism with the number of workers per office room. In both articles the analysis was adjusted for relevant confounders. Tables 5 and 6 give the results. In the second study the two-person room does not show lower absenteeism than larger rooms. The one-person room does show some 30% lower absenteeism. In the third study single person rooms and two to three person rooms show some 40% resp. 30% lower short term absenteeism than open plan offices. Although these results are not entirely consistent, they indicate that housing in one to three person offices is about a factor 3 more effective than doubling the ventilation rate in an open plan office.

---

[2] The lower long-term absenteeism in the case of an area with registered complaints cannot be accounted for with the given data, but in any case it does not refute the assumption that workers' dissatisfaction increases short-term rather than long-term absenteeism.

Table 4. Multivariate analysis of characteristics associated with self reported absenteeism. Adapted from Preller et al. (1990a).

Odds ratios, 95% CI	General absenteeism		Absenteeism assigned by the worker to work related complaints	
Characteristics No versus yes	Number of sick leaves, >1 vs. ≤	Number of days, >1 vs. ≤	Number of sick leaves, >1 vs. ≤	Number of days, >1 vs. ≤
Spray humidifier	0.77 0.62 – 0.95	0.75 0.61 – 0,93	0.64 0.46 – 0.88	0.77 0.60 – 1.00
Steam humidifier	0.78 0.64 – 0.96	0.80 0.65 – 0.98	0.51 0.37 – 0.69	0.70 0.55 – 0.89
Satisfied with IEQ complaint handling	1.56 1.36 – 1.78	1.48 1.30 – 1.70	2.16 1.79 – 2.60	1.86 1.60 – 2.16

Table 5. Multivariate analysis of association of self reported absenteeism with the number of workers per office room. Adapted from Pejtersen et al. (2011).

Number of workers	1	2	3-6	>6
Odds ratios, 95% CI	1	1.50 1.13-1.98	1.36 1.08-1.73	1.62 1.30-2.02

Table 6. Multivariate analysis of association of self reported short term absenteeism with the number of workers per office room. Adapted from Bodin Danielsson et al. (2014).

Number of workers	1	2-3	4-9	10-24	>24
Odds ratios, 95% CI	1	1.23 0.81-1.86	1.90 1.16-3.10	1.92 1.08-3.40	1.82 1.14-2.88

9 Discussion and conclusions

The Rehva Guide states that its main purpose is to establish quantitative relationships of indoor environmental aspects with performance and absenteeism[3]. The purpose of this paper is to establish what in practice are, or probably are, the most effective measures to increase performance and reduce absenteeism, given the total of the presently available evidence. Pursuing this purpose we come to the following conclusions:

---

[3] The authors of the Rehva Guide have decided not to establish qualitative relationships due to a "*very* high level of uncertainty" (italics added) they suppose them to have. At the same time, concerning the main quantitative relationships established in the Rehva Guide (temperature with performance, ventilation with performance and ventilation with absenteeism) the publications on which these relationships are based (Seppänen et al., 2006a, Seppänen et al., 2006b, Fisk et al., 2003) state that these relationships have a high level of uncertainty, that, however, use of these relationships may be preferable to current practice, which ignores productivity. We feel that qualitative relationships or relationships based on dichotomous variables can be just as relevant for design decisions as quantitative relationships and do not necessarily have a high level of uncertainty. When one considers the total of presently available evidence measures like cellular workroom layout combined with shallow plan depth or avoidance of indoor air pollution sources, including HVAC components, building materials and office equipment, have a relatively good chance of substantially improving workers' performance and reducing absenteeism. Given the present state of knowledge the decision not to establish qualitative relationships causes the Rehva Guide to be biased in favour of measures that often have a relatively low effect, have a high level of uncertainty and will in most cases increase energy consumption, and to be biased against measures that can have a relatively high effect, have a relatively low level of uncertainty and will in many cases reduce energy consumption (see the end of section 9).

Concerning the impact of temperature on performance:

- The relationship presented in the Rehva Guide, where performance is maximal at 21.75˚C, cannot be extrapolated to free running environments.
- In free running environments we expect performance to be maximal at the matching comfort temperature, which can be considerably higher than 21.75˚C.
- When it comes to comparing air conditioned environments at the matching comfort temperature and free funning environments at the matching comfort temperature, we expect performance to be higher in free running environments because therein occupant satisfaction with the indoor environment will be higher and BRS, including fatigue, headache and problems concentrating, will be less.

Concerning the impact of ventilation on performance:

- Strict avoidance of indoor air pollution sources is more effective (a factor 10 or more) in raising performance than increasing the ventilation rate above 10 l/s*person.
- Housing in small (two-person) cellular offices with occupant control of temperature is more effective (a factor 3 to 15 or more) in raising performance than increasing the ventilation rate above 10 l/s*person.
- Avoidance of pollution sources and housing in cellular offices have a high probability of increasing performance and will have no negative side effects. Increasing the ventilation rate may result in lower performance when there are pollution sources in the HVAC system or when there are pollutants in the indoor air that are sensitive to oxidation and increased ventilation rate increases the indoor concentration of ozone.

Concerning the impact of ventilation on absenteeism:

- The relation of absenteeism with ventilation rate in the Rehva Guide and the results of Jaakkola and Heinonen (1995) imply that avoiding open plan offices and recirculation is at least an effective alternative to increasing ventilation rate when it comes to reducing absenteeism. The studies concerning the relation of self reported absenteeism with the number of workers per office room indicate that housing in one to three person offices is more effective (about a factor 3) than doubling the ventilation rate in an open plan office.
- Avoiding a typical indoor air pollution source like a humidifier is about as effective as doubling the ventilation rate from approximately 12 to approximately 24 l/s*person. Avoidance of several or all pollution sources may be more effective than that.
- All measures which improve workers' satisfaction with the indoor environment, including those which are unrelated to infection risk or indoor air quality, will lower absenteeism because the improved satisfaction will increase workers' loyalty to the organisation and thereby decrease both the probability of reporting ill and the probability of postponing reporting well in case of non serious illness.

In Leyten and Kurvers (2006) Leyten, Kurvers and Van den Eijnde (2009) and Leyten and Kurvers (2011) the authors of this paper have argued that workers' satisfaction with the indoor environment is for an important part determined by the *robustness* of the building. Robustness is defined as the measure by which the IEQ delivered by the building lives up to its design purpose when it is used by occupants in a real life situation. According to these publications examples of robust measures are:

- Avoidance of indoor air pollution sources in the workrooms and in the HVAC system.
- Minimizing external and internal heat load.
- Using thermal effective building mass.
- Housing in cellular offices combined with shallow plan depth.
- Occupant control of temperature.
- Operable windows which the workers can open and adjust at will.
- Offering a comfortable thermal environment without mechanical cooling, using adaptive thermal comfort

Examples of less robust measures are:
- Diluting indoor air pollution through increased ventilation instead of avoiding pollution sources.
- Controlling temperature through mechanical cooling instead of reducing external and internal heat load, using thermal effective building mass and offering the occupants adaptive opportunities.
- Open plan workroom layout combined with deep plan depth.

Leyten and Kurvers (2006), Leyten, Kurvers and van den Eijnde (2009) and Leyten and Kurvers (2011) intended to show that robust measures, especially when combined, are likely to result in much more occupant health and satisfaction than less robust measures. This paper intends to show that robust measures are more effective in increasing objectively measured workers' performance and in reducing sickness absenteeism than less robust measures.
If one is prepared to accept large effects concerning self reported performance as indicators of objective performance, this argument can be pressed one step further. One important robust measure that we discussed in Leyten, Kurvers and van den Eijnde (2009) is offering the occupants an environmental *Gestalt* that promotes acceptance. This is the case if the following conditions apply simultaneously:
- Aberrations from "comfortable", "preferred" or "neutral" can be reduced or compensated for by the occupants in a feasible way and without negative side effects for themselves or others. This includes control of the environment and control of personal factors like activity and clothing. If there are negative side effects the control opportunities should allow for trading off positive and negative results of choices against one another.
- Remaining aberrations from "comfortable", "preferred" or "neutral" are understandable on the basis of transparency of the functioning of the building and its systems to the occupants.
- Remaining aberrations from "comfortable", "preferred" or "neutral" are judged equitable by the occupants on the basis of understanding the aberrations and on the basis of perceived co-responsibility for the environment through occupant control. (Transparency concerns the working of the building system; understanding concerns the aberrations).

This may seem a rather abstract concept, but there exits a vey good proxy measure for it. In their presentation "Are building users more tolerant of 'green' buildings" Adrian Leaman and Bill Bordass introduce the concept of "forgiveness" which is the measure by which occupants positively value the indoor environment as a whole despite individual shortcomings because the indoor environment as a whole promotes satisfaction. They derive a forgiveness score for a given building by dividing the average score given by the occupants for “comfort overall” by the average of the scores given for temperature in summer and winter, ventilation/air in summer and winter, noise and lightning. Scores above 1.0 indicate a higher level of forgiveness. In our view forgiveness defined in this way is an excellent empirical measure of what we have called the acceptance promoting environmental *Gestalt*. Figure 5 shows the results of a set of “green” and conventional buildings from the UK. (A set of Australian buildings shows very similar results). The correlation of self reported performance with forgiveness is strong: 0.75. The performance score of the buildings with the highest forgiveness score is some 20% higher than of the buildings with the lowest forgiveness score. So even an abstract robust measure like the acceptance promoting *Gestalt* can be shown to raise performance. Furthermore the acceptance promoting *Gestalt*, or in other words forgiveness, is also expected to improve workers’ loyalty and thus to decrease both the probability of reporting ill and the probability of postponing reporting well in case of non serious illness.

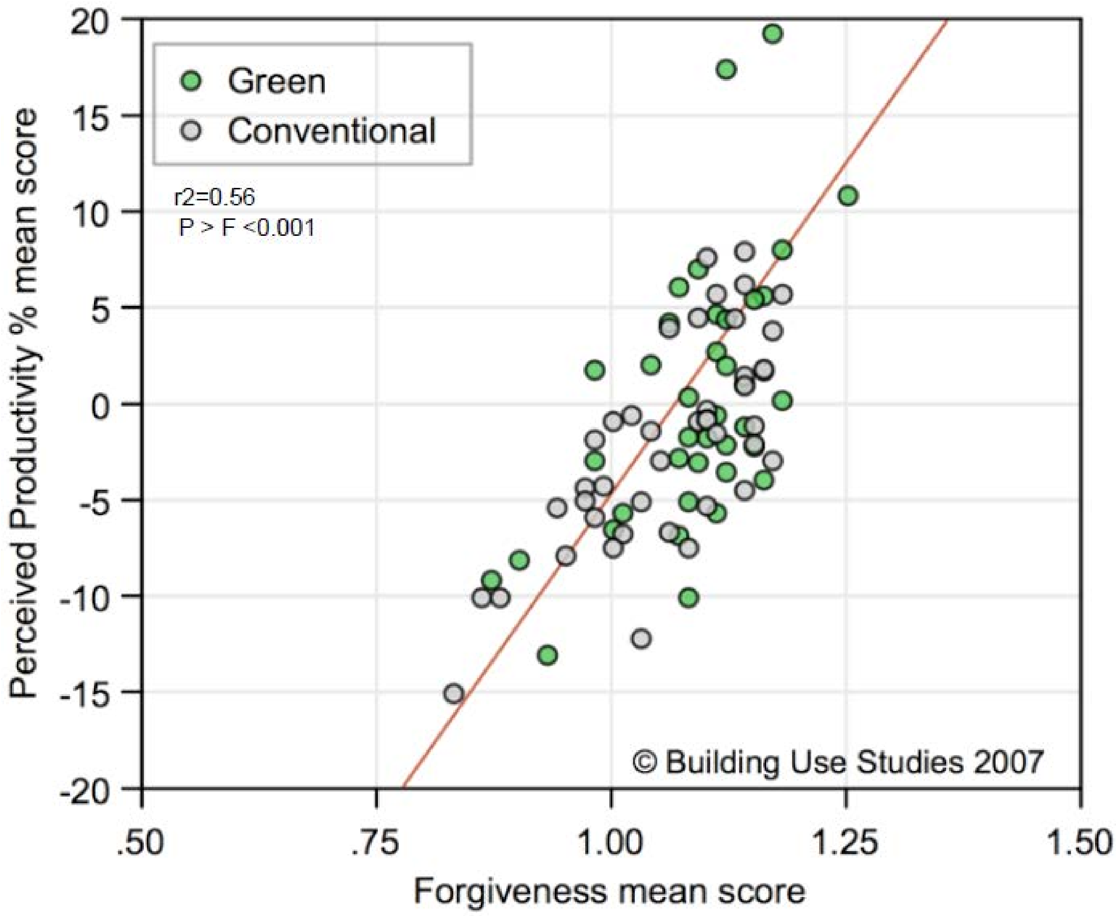

Figure 5: Forgiveness and perceived productivity. Source: presentation “Are building users more tolerant of ‘green’ buildings” by Adrian Leaman and Bill Bordass.

Since data concerning performance and absenteeism are important objectively measurable indicators of IEQ and these data were not used in forming the building robustness hypothesis in our earlier publications, we consider these results an important independent corroboration of the building robustness hypothesis.

Although we have not yet developed this in detail, an extension of the building robustness hypothesis is that robust measures as we define them not only promote health, comfort and productivity, but also lead to lower energy consumption. A few points to make this plausible:

- Roulet (2006) argues that to achieve both good IEQ and low energy consumption one should control the indoor environment as much as possible through passive measures and apply active measures only to fine-tune the indoor environment where necessary. Important instances of this strategy are control of indoor air pollution sources instead of relying on increased ventilation and temperature control through control of heat sources and building physics instead of relying on mechanical cooling.
- Knudsen and Wargocki (2010) confirm that control of indoor air pollution sources instead of relying on increased ventilation lowers energy consumption.
- Offering a comfortable thermal environment without mechanical cooling using adaptive thermal comfort will, when well applied, lower energy consumption.
- The combination of cellular workroom layout and shallow plan depth allows for natural ventilation or else simple mechanical ventilation instead of more energy consuming elaborate HVAC systems.
- Kurvers et al. (2013) is a preliminary study using two databases: one Dutch database that includes predicted and actual energy use of a set of buildings, and the European Hope database that includes health and comfort scores. Next to that both databases include building characteristics. In this study, the buildings were devided into nine typologies. The results show that the buildings with a combination of characteristics denoted as "climate oriented" had the lowest energy consumption as well as the lowest Building Symptoms Index, whereas the building type "climate ignoring" showd higher energy consumption as well as a higher Building Symptom Index.

References

Alm, O., Clausen, G., Fanger, P.O., 2000. Exposure-response relationships for emissions from used ventilation filters. In: ISIAQ *Proceedings Healthy Buildings 2000*. Espoo, Finland, 6 – 10 August, 2000.

Bakó-Biro, Z., 2004. *Human perception, SBS symptoms and performance of office work during exposure to air polluted by building materials and personal computers*. Ph.D. Technical University Denmark.

Bluyssen, P.M., Cox, C., Seppänen, O., Oliveira Fernandes, E. de, Clausen, G., Müller, B., Roulet, C.A., 2003. Why, when and how do HVAC-systems pollute the indoor environment and what to do about it? The European AIRLESS project. *Building and Environment*, 38, pp 209-225.

Bodin Danielsson, C., Singh Chungkham, S., Wulff, C., Westerlund, H., 2014. Office design's impact on sick leave rates. *Ergonomics*, DOI: 10.1080/00140139.2013.871064.

Brashe, S., Bullinger, M., Morfeld, M., Gebhart, H.J., Bischof, W., 2001. Why do women suffer more from sick building syndrome than men? - Subjective higher sensitivity versus objective causes. *Indoor Air*, 11(4), pp 217-222.

de Dear, R., Brager, G., Cooper, D., 1997. *Developing an adaptive model of thermal comfort and preference*. ASHRAE RP-884.

Fitzner, K., 2000. Control of pollutants in air handling systems. In: ISIAQ *Proceedings of Healthy Buildings 2000*. Espoo, Finland, 6 – 10 August, 2000.

Fisk, W.J., Mendell, M.J., Daisey, J.M., Faulkner, D., Hodgson, A.T., Nematollahi, M., Macher, J.M., 1993. Phase 1 of the California Healthy Buildings Study: a Summary. *Indoor Air*, 3, pp 246 - 254.
Fisk, W., Seppänen, O., Faulkner, D., Huang, J., 2003. Economizer system cost effectiveness: accounting for the influence of ventilation rate on sick leave. In: ISIAQ *Proceedings Healthy Buildings 2003 – Energy Efficient Healthy Buildings*. Singapore, 7 – 11 December 2003.
Frontczak, M., Schiavon, S., Goins, J., Arens., E, Zhang, H., Wargocki, P., 2012. Quantitative relationships between occupant satisfaction and satisfaction aspects of indoor environmental quality and building design. *Indoor Air*, 22(2), pp 119-131.
Heschong Mahony Group, 2003. *Windows and offices: A study of office worker performance and the indoor environment – Technical Report*. California Energy Commission.
Hongisto, V., 2005. A model predicting the effect of speech of varying intelligibility on work performance. *Indoor Air*, 15(6), pp 458-468.
Jaakkola, J.J.K., Heinonen, O.P., 1995. Shared office space and the risk of the common cold. *European Journal of Epidemiology*, 11, pp 213-216.
Kroner, W.M., Stark-Martin, J.A., 1994. Environmentally responsive workstations and office-worker productivity. *ASHRAE Transactions*, 100(2), pp 750-755.
Knudsen, H.N., Wargocki, P., 2010. Strategy for good perceived air quality in sustainable buildings. In: REHVA *Proceedinsg Clima 2010, 10th REVHA World Congress 'Sustainable Energy Use in Buildings'*, Antalya, Turkey, 9 – 12 May, 2010: Turkish Society of HVAC & Sanitary Engineers.
Kurvers, S.R., Raue, A.K., Ham, E.R. van den, Leyten, J.L., Juricic, S.M.M., 2013. Robust climate design combines energy efficiency with occupant health and comfort. *ASHRAE IAQ 2013 Proceedings: Environmental Health in Low-Energy Buildings.* Vancouver, Canada, 15 – 18 October, 2013, Atlanta GA: ASHRAE.
Leyten, J.L., Kurvers, S.R., 2006. Robustness of buildings and HVAC systems as a hypothetical construct explaining differences in building related health and comfort symptoms and complaint rates. *Energy and Buildings*, 38, pp 701-707.
Leyten, J.L., Kurvers, S.R., van de Eijnde, J., 2009. Robustness of office buildings and the environmental Gestalt. In: *Santanam, S., Bogucz, E.A., Peters, C., and Benson, T., Healthy Buildings 2009 Proceedings of the 9th International Healthy Buildings Conference and Exhibition.* Syracuse, NY, USA, 13 – 17 September 2009, ISIAQ.
Leyten, J.L., Kurvers, S.R., 2011. Robust indoor climate design. In: ISIAQ *Proceedings Indoor Air 2011*. Austin, USA, 5 – 10 June, 2011, ISIAQ.
Milton D.K., Glencross P.M., Waters M.D., 2000. Risk of sick leave associated with outdoorair supply rate, humidification and occupant complaints. *Indoor Air*, 10, pp 212-221.
Nicol, F., Humphreys, M., 2005. Adaptive comfort in Europe: results from the SCATs survey with special reference to free running buildings. In: *Proceedings of the international conference on EPDB Energy Performance of Buildings Directive: implementation in practice*, Brussels, 21 – 23 September 2005.
Oversloot J., 1995. *Verzuimbeheersing (Absenteeism Control).* The Netherlands: Delwel.
Pejtersen, J., Allerman, L., Kristensen, T.S., Sjostrom, M., 2006. Indoor climate, psychosocial work environment and symptoms in open-plan offices. *Indoor Air*, 16(5), pp 392-401.

Pejtersen, J., Feivelle, H., Christensen, K.B., Burr, H., 2011. Sickness absence associated with shared and open plan offices – a national cross sectional questionnaire survey. *Scand J Work Environ Health*, 37(5), pp 376-382.
Preller, L., Zweers, T., Boleij, J., Brunekreef, B., 1990a. *Gezondheidsklachten en klachten over het binnenklimaat in kantoorgebouwen*. The Netherlands: Directoraat-Generaal van de Arbeid. (The original Dutch publication of the study reported in Preller et al., 1990b)
Preller, L., Zweers, T., Brunekreef, B., Boleij, J., 1990b. Sick leave due to work-related health complaints among office workers in the Netherlands. In: ISIAQ Indoor Air '90, *Proceedings of the 5th International Conference on Indoor Air Quality and Climate*. Toronto, Canada, July 29 – August 3 1990.
Raw, G.J., Roys, M.S., Leaman, A., 1990. Further findings from the office environment survey: productivity. In: ISIAQ Indoor Air '90, *Proceedings of the 5th International Conference on Indoor Air Quality and Climate*. Toronto, Canada, July 29 – August 3 1990.
Robertson A.S., Roberts K.T., Burge P.S., Raw G., 1990. Effect of change in building ventilation category on sickness absence rates and the prevalence of sick building syndrome. In: ISIAQ Indoor Air '90, *Proceedings of the 5th International Conference on Indoor Air Quality and Climate*. Toronto, Canada, July 29 – August 3 1990.
Roulet, C.A., 2006. Indoor air quality and energy performance of buildings. In: E. de Oliveira Fernandes, M. Gameiro da Silva, J. Rosado Pinto, *HB 2006 healthy buildings - Creating a healthy indoor environment for people - Proceedings.* Lisboa, Portugal, 4 – 8 June 2006, ISIAQ.
Seppänen, O., Fisk, W.J., Lei, Q.H., 2006a. Effect of temperature on task performance in office environment. In: *Cold Climate HVAC 2006, Proceedings of The 5th International Conference on Cold Climate - Heating, Ventilating and Air-Conditioning*. Moscow, Russia, 21 – 24 May 2006, Moscow, Russia: Russian Association of Engineers for Heating, Ventilation, Air-Conditioning, Heat Supply & Building Thermal Physics (ABOK).
Seppänen, O., Fisk, W.J., Lei, Q.H., 2006b. Ventilation and performance in office work. *Indoor Air*, 16(1), pp 28-35.
Strøm-Tejsen, P., Clausen, G., Toftum, J., 2003. Sensory pollution load from a used ventilation filter at different air flow rates. In: ISIAQ *Proceedings Healthy Buildings 2003 – Energy Efficient Healthy Buildings*. Singapore, 7 – 11 December 2003.
Wargocki, P., Wyon, D.P., Fanger, P.O., 2004. The performance and subjective responses of call-centre operators with new and used supply air filters at two outdoor air supply rates. *Indoor Air*, 14(Suppl 8), pp 7-16.
Wilson, S., Hedge, A., 1987. *The Office Environment Study - A Study of Building Sickness*. Building Use Studies Ltd, London.
Wyon, D.P., 2000. Individual control at each workplace: the means and the potential benefits. In: Clements-Croome, D (ed.), *Creating the productive workplace*. London: E & FN SPON, pp 192-206.
Zweers, T., Preller, L., Brunekreef, B., Boleij, J.S.M., 1992. Health and Indoor Climate Complaints of 7043 Office Workers in 61 Buildings in the Netherlands. *Indoor Air*, 2(1), pp 127-136.