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Robust Design as a Strategy for higher workers' productivity – A reaction to Rehva Guide No 6 Indoor Climate and Productivity in Offices

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Summary
Rehva Guide No 6 – Indoor Climate and Productivity in Offices - states as its main purpose to establish quantitative relationships of indoor environmental aspects with productivity and sickness absenteeism. The following relationships were established: temperature with productivity, ventilation with productivity, perceived indoor air quality with productivity 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 productivity 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, occupant control of temperature, operable windows and providing for adaptive thermal comfort are more effective in increasing productivity and reducing absenteeism than less robust measures like diluting indoor air pollution through increased ventilation or controlling temperature through mechanical cooling.

Keywords: Productivity, sickness absenteeism, adaptive thermal comfort, indoor air quality, building robustness.

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 productivity and sickness absenteeism. The following relationships were established: temperature with productivity, ventilation with productivity, perceived indoor air quality with productivity 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 productivity and decrease absenteeism, given the total of the presently available evidence.

Temperature and productivity
The Rehva Guide presents a meta-analysis of studies concerning the impact of temperature on productivity. Figure 1 shows the results of the meta-analysis. If the curve weighted by sample size and outcome relevance is selected productivity is maximal at a temperature of 21.75˚C. Above and below this temperature productivity decreases with approximately 1.5% per ˚C. If

this relationship would be valid for free running environments, at an indoor temperature of for instance 28˚C productivity would be 6% lower than in an air conditioned environment at 22˚C.

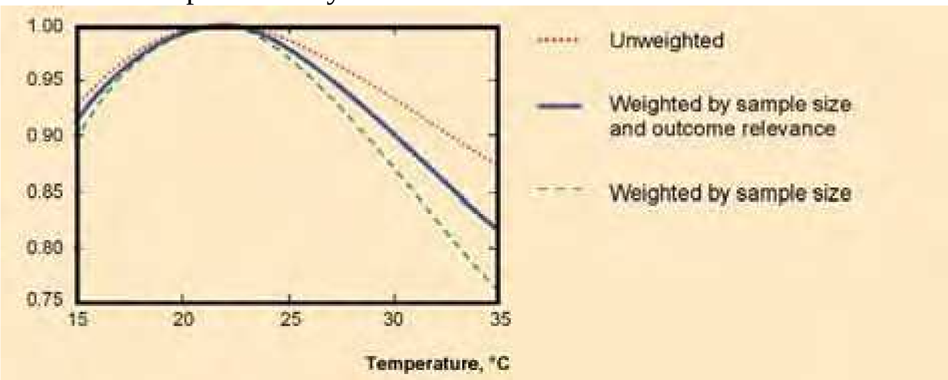

Figure 1: Relative performance vs. temperature. Maximum performance is set equal to 1.

To determine whether the relationship in the Rehva Guide is representative for free running environments the original studies on which the meta-analysis is based have been examined, in some cases through Seppänen et al. (2003) or Seppänen et al. (2006a), on which the relationship in the Rehva Guide is based. It turns out that of 24 separate studies 14 are experimental studies in a climate chamber or laboratory, 8 studies were conducted in air conditioned office buildings, one was conducted in a mechanically ventilated office building without mechanical cooling and with sealed windows and one in an apparel factory without mechanical cooling. From the 24 original studies 22 concern air conditioned environments and so the relation in the Rehva Guide is representative for air conditioned environments. None of the 24 studies is representative for a free running office environment. Whether the relation in the Rehva Guide is representative for free running environments cannot be established on basis of the Rehva Guide or other data. We have found no studies concerning the impact of temperature on productivity in free running environments. But the following points can be stated:
- It has been empirically established that workers in a free running office environment judge thermal comfort in a way that is different from an air conditioned environment (e.g. De Dear et al., 1997). During the summer period the comfort temperature in free running environments is higher than in air conditioned environments. If these two kinds of environments are so different when it concerns thermal comfort, it cannot be excluded that they also differ when it concerns the impact of temperature on productivity. So without further data the relation in the Rehva Guide cannot be held valid for free running environments.
- The temperature range in the Rehva Guide with maximal productivity conforms very closely to the comfortable temperature range in air conditioned office environments according to the PMV model. This may indicate that in free running environments productivity is maximal at the neutral temperature in a free running environment, which during the summer period, or in warmer climates, may be higher than the neutral temperature specified by the PMV model.
- Nishihara et al. (2007) is a Japanese field study concerning the productivity of programmers in an air conditioned environment. Figure 2 show that the neutral temperature is 28.6˚C. This relatively high neutral temperature is explained by Nishihara et al. (2007) by a relatively high air velocity of 0.2 – 0.4 m/s and the fact that the workers could freely adjust their clothing.

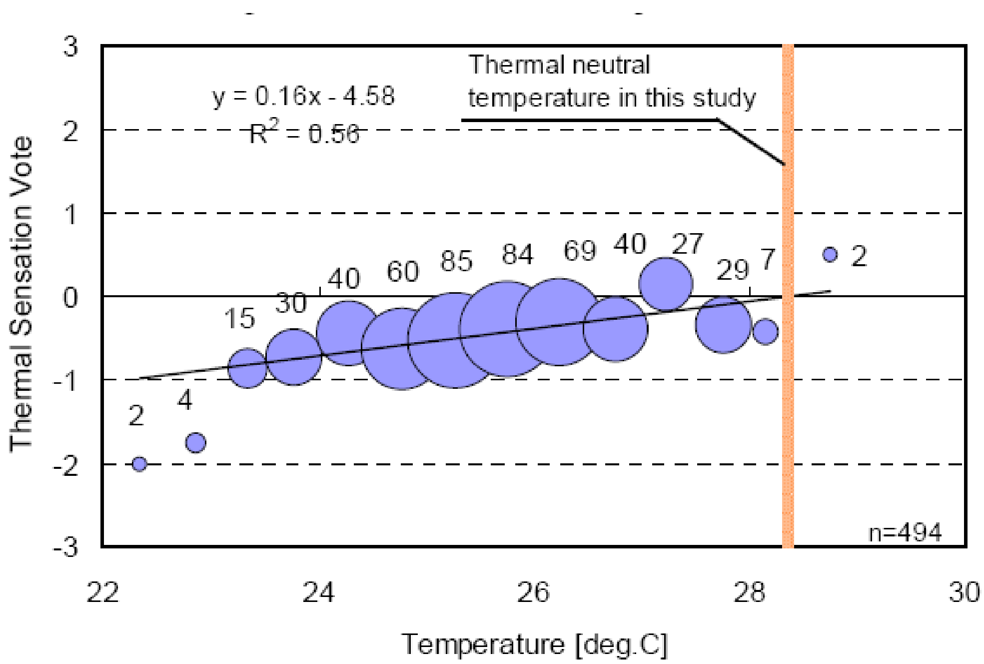

Figure 2: The relationship of air temperature and thermal sensation vote.

Figure 3 shows the relation between temperature and productivity objectively measured as the number of keyboard strokes per workday. Productivity is highest at the neutral temperature and decreases with 7.8% per ˚C under the neutral temperature.

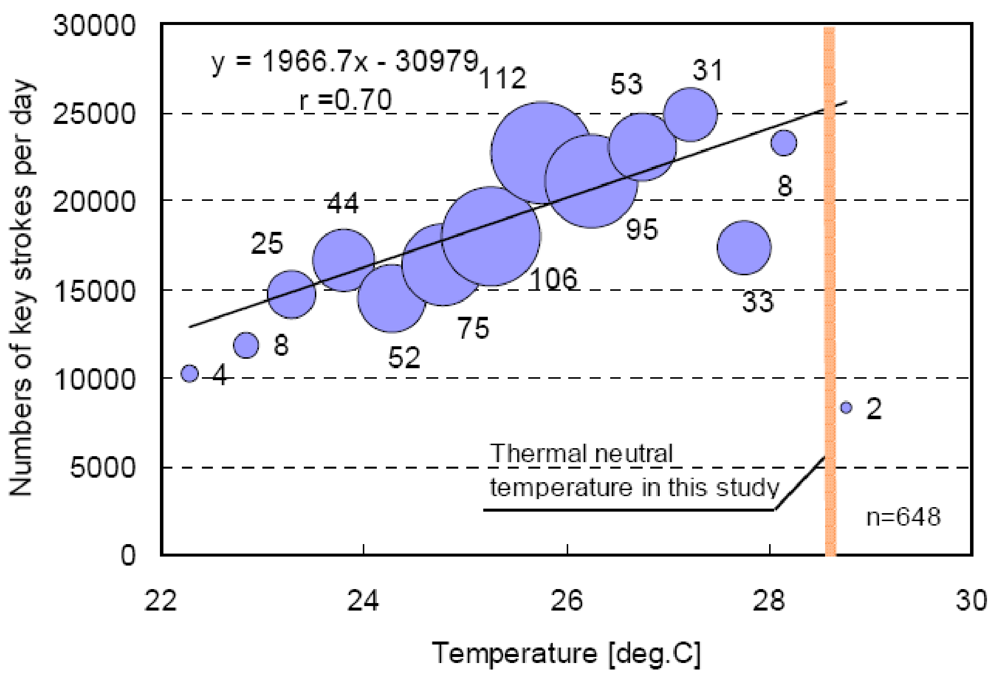

Figure 3: Air temperature and the number of keystrokes per day

- McCartney & Humphreys (2002) is a field study in 25 office buildings in several European countries. Among other things temperature at the workplace was measured, workers were asked about their thermal preference and about the impact of the work environment on their own productivity as judged by themselves. The impact of the work environment on the productivity of office workers as judged by themselves does not correlate with measured temperature (figure 4) but does correlate with thermal preference (figure 5).

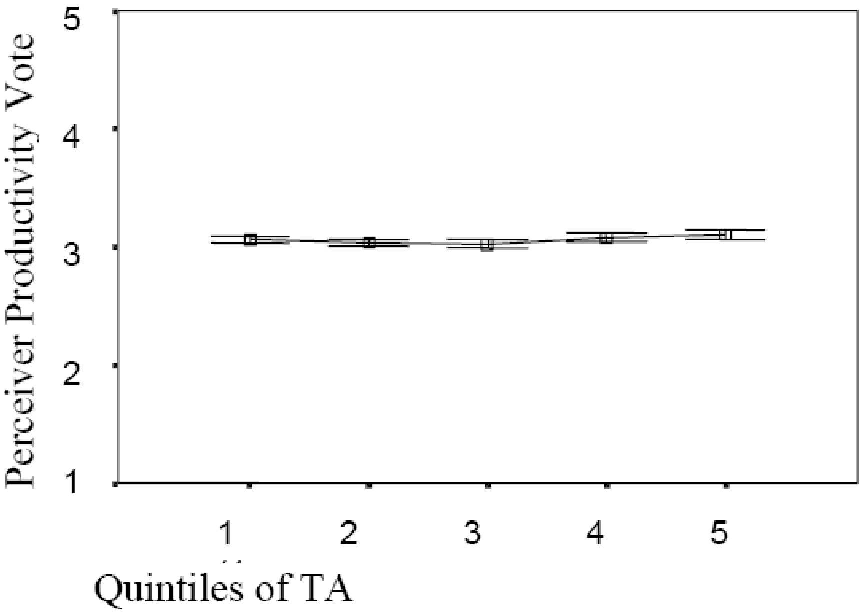

Figure 4: Perceived Productivity Vote versus Quintiles of Air Temperature, TA. (Note that the higher the Perceived Productivity Vote, the lower perceived productivity. The error bars represent the 95% confidence range of the productivity vote. The quintiles of air temperature represent an overall range of approximately 13.1°C to 31.1°C with categories as follows: 1(13.1 – 21.9°C), 2 (21.9 – 23.0°C), 3 (23.0 – 23.9°C), 4 (23.9 – 25.2°C), 5 (25.2 – 31.1°C)).

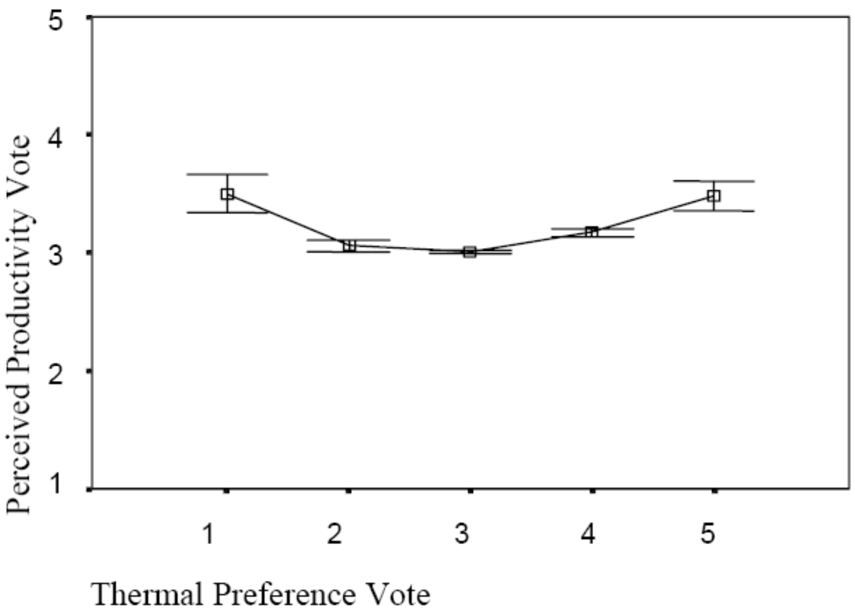

Figure 5: Perceived Productivity Vote versus Thermal Preference Vote, TP. (Note that TP scale goes from 1 to 5, Much Warmer to Much Cooler, with 3 No Change).

- Ueki et al, (2007) is an experimental study in which subjects perform mathematical tasks during 360 minutes under three different thermal conditions: T=25˚C and clo=0.93, T=28˚C and clo=0.93 and T=28˚C and clo=0.57. There is no difference between the conditions in objectively measured performance, but performance was lower in the case of lower satisfaction with the environment.

- Haneda et al. (2008) is an experimental study in which subjects perform mathematical tasks during 350 minutes and both temperature (T=25˚C or T=28˚C) and ventilation rate (3 or 25 l/s*p) are varied. There is no difference between the conditions in objectively measured performance, but performance was lower in the case of lower satisfaction with the environment.[1]

The best fitting generalisation that can be drawn from the above mentioned studies is that in a given environment productivity is highest when workers experience the environment as maximally comfortable and that productivity decreases when the environment is experienced as less comfortable. If this is also true for free running environments, then herein productivity is highest at the neutral or comfortable temperature, which can be higher than predicted by the PMV model, and productivity decreases when the temperature deviates from neutral.

That leaves the question in which environment the productivity is higher, in an air conditioned environment with the matching comfort temperature (approximately 22˚C) or a free running environment with the matching comfort temperature, assuming that all other conditions are equal. There are no data which can answer this directly, but the following can be stated: In air conditioned environments the prevalence of building related symptoms, including headache, fatigue and difficulty concentrating, is higher than in free running environments (Mendell & Smith, 1990, Seppänen & Fisk, 2002). The same goes for dissatisfaction with the thermal environment and indoor air quality (e.g. Zweers et al, 1992, Teeuw, 1993, Groes, 1995, Bischof et al., 2004). Headache, fatigue and difficulty concentrating cause lower productivity (Tanabe & Nishihara, 2004). The same goes for dissatisfaction with the indoor air quality (see the Rehva Guide) and the thermal environment (see the studies mentioned above). If the generalisation that productivity is maximal in an environment that is experienced as most comfortable is true, then probably productivity in free running environments with the matching comfort temperature is higher than in air conditioned environments with the matching comfort temperature.

Ventilation rate and productivity

The Rehva Guide gives a relation between ventilation rate and productivity based on five field studies in offices and two laboratory studies. The results are given in figure 6 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 productivity increases with 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 productivity increases statistically significantly in the ventilation range of 6.5 to 17 l/s*p with 90% CI and up to 15 l/s*p with 95% CI. Even if we leniently choose the 90% CI, there is no statistically significant

[1] Most of the studies cited in this paper concern a measure of productivity that is representative for some sort of office work and is quantifiable. Examples are the number of processed calls during a certain time in a call center (e.g. Wargocki er al., 2003), time needed to process a given text (e.g. Bakó-Biró, 2004) or number of keyboard strokes during one workday in the case of programming (e.g. Nishihara et al., 2007). These give quantitative indicators of productivity and allow for expressing productivity gain or loss in percentages. Ueki et al. (2007) and Haneda et al. (2008) present the subjects with a large number of mathematical tasks during a fixed period of time and define performance as the number of correct answers per period of time, which produces a sort of combination of performance and productivity. These cannot be expressed directly in percentages of productivity loss or gain, but can be used to support the generalisation that in a given environment productivity is highest when workers experience the environment as maximally comfortable and that productivity decreases when the environment is experienced as less comfortable.

effect above 17 l/s*p, which implies that the maximum productivity gain that can be reached by increasing the ventilation rate above 10 l/s*p is 1%.

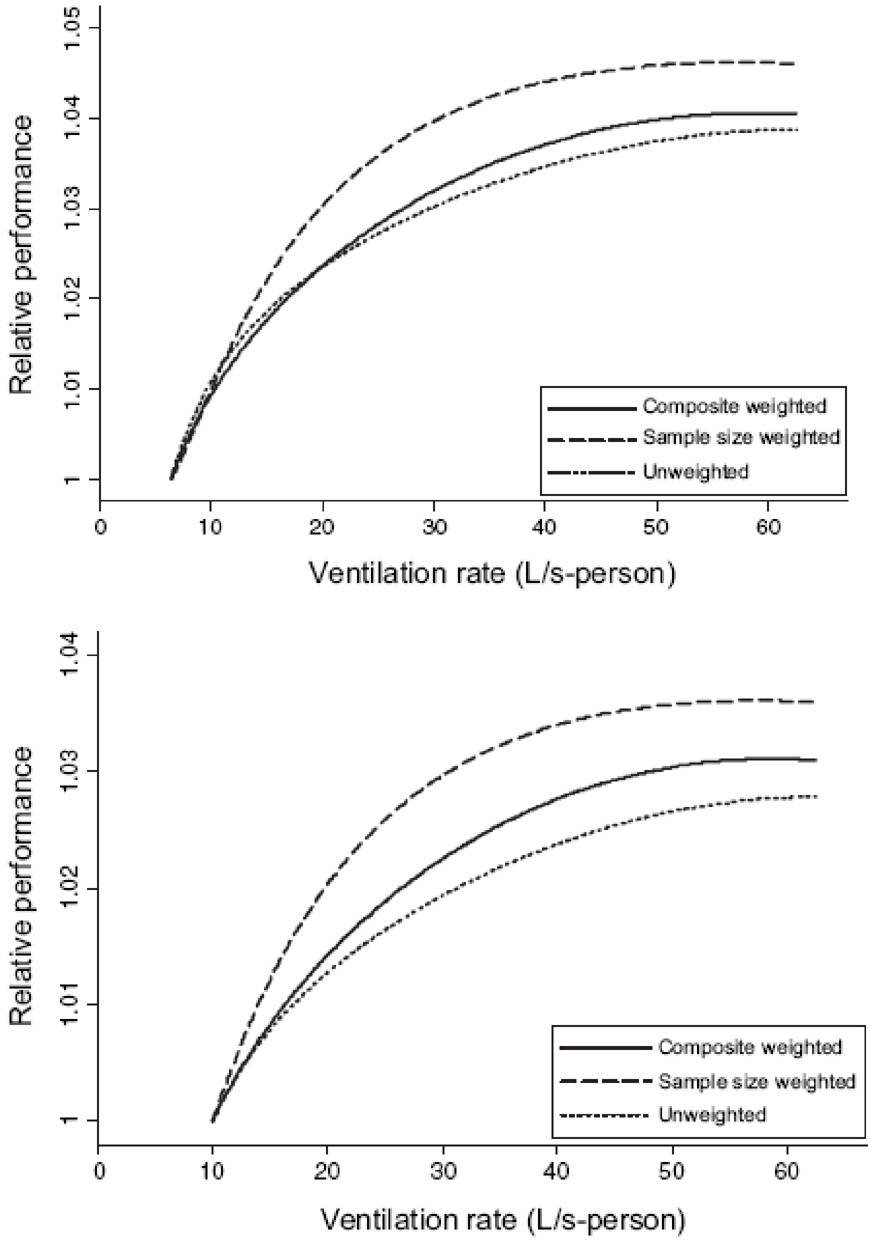

Figure 2: Relative performance in relation to the reference values 6.5 l/s-person (upper) and 10 l/s-person (lower) vs. ventilation rate.

Alternatives to increasing ventilation rate

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

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

The Rehva Guide gives two relations of productivity with percentage dissatisfied with air quality, one of 1.1% productivity gain for each 10% less dissatisfied with indoor air quality and one of 0.8% productivity gain for each 10% less dissatisfied with indoor air quality. Since these relations are based on slightly different, overlapping data, we propose a simplified relation of 1% productivity gain for each 10% less dissatisfied with indoor air quality. This relation implies some additivity of the effect of pollution sources. Furthermore Fitzner (2000) shows that pollution source strength of other components of HVAC systems, like a cooling section, a humidification section and a rotary heat exchanger is comparable with that of air intake filters. Therefore it is safe to expect that a strict avoidance of indoor air pollution sources in both the HVAC system and the workrooms will result in a productivity gain of 10% or more, when compared to currant practice.

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	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 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 & Hedge (1987), Zweers et al. (1992), Fisk et al. (1993) and Brasche et al. (2001). So, another way to increase productivity is to house workers in cellular offices instead of in open plan offices.

The effect of thermal discomfort is difficult to quantify because there is no direct relation of 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[2] 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% productivity 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 productivity with STI (Speech Transmission Index) based on a large number of studies from which it can be deduced that productivity 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 7).

[2] Perception of dry air relates to indoor air pollutants rather than low air humidity

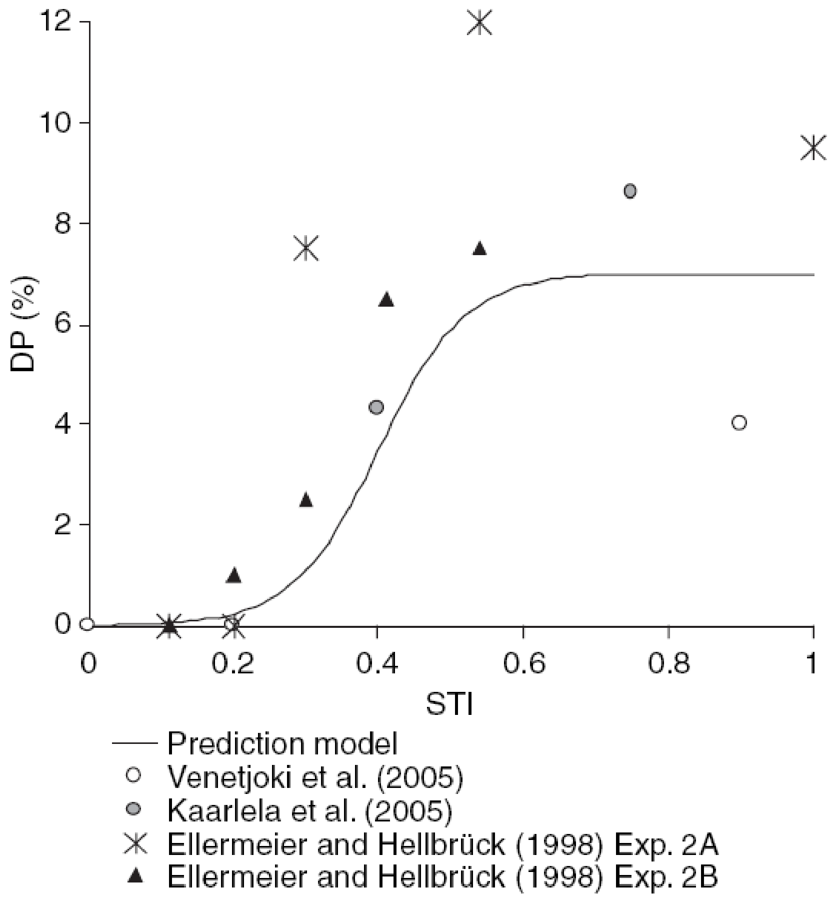

Figure 7: The schematic prediction model, which gives the decrease in performance, DP, as a function of the STI. The highest performance is obtained when no speech is heard (STI ¼ 0.00, conventional office) and the highest performance decrease is reached when speech is highly intelligible (STI > 0.70,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

The effects of lighting and reflections and of BRS cannot be quantified with present knowledge, but some effect is expected.

Furthermore 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 productivity 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 productivity 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% productivity loss, possibly plus the unknown effects of dissatisfaction about lighting and reflections 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 productivity, the effects of open plan offices and of lack of occupant control are independent, so some additivity between the two is expected.

The above shows that avoidance of indoor air pollution sources and housing in cellular offices are more effective in increasing productivity 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. (2003), a field study, shows that when the ventilation level is increased in the case of used, polluted filters increased ventilation leads to a decrease of the perceived indoor air quality and of productivity. A similar effect on perceived indoor air quality is found by Strøm-Tejsen et al. (2003). The conclusion is that the increased ventilation leads to higher emission of pollutants from the polluted filters. 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 with pollutants in the indoor air that are sensitive to oxidation, like terpenes, emission of pollutants increases with increased ventilation when 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.

Ventilation rate and sickness absenteeism

The Rehva Guide presents a quantitative relationship between ventilation rate and short-term sickness absenteeism (from hereon: absenteeism) by combining published field data and a theoretical model of airborne transmission of respiratory infections based on the Wells-Riley equation (for more information see: Fisk et al., 2003). The result is given in figure 8.

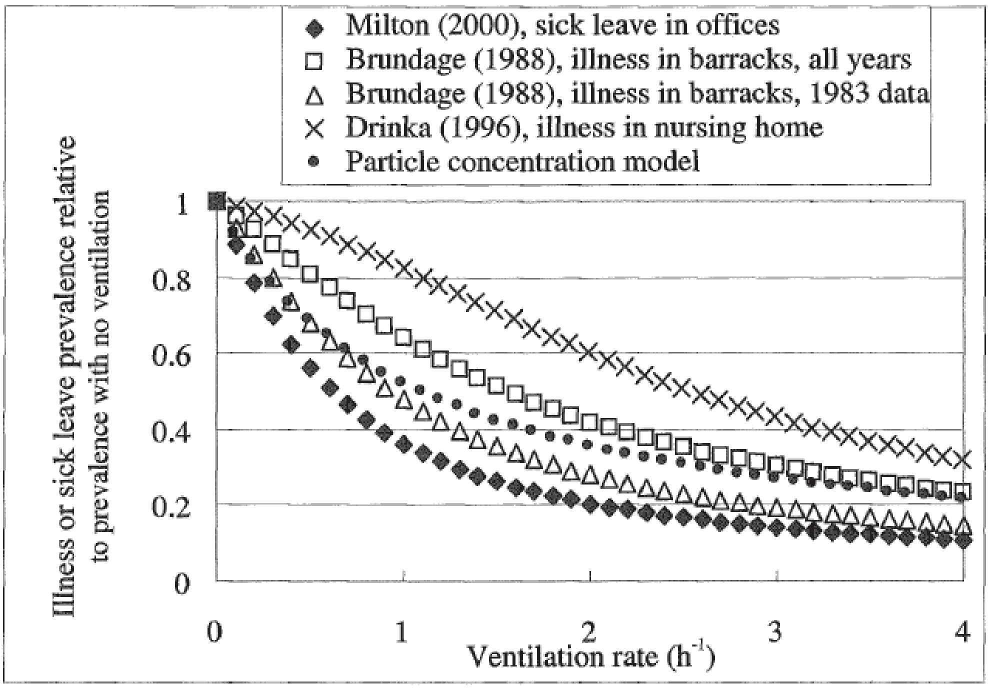

Figure 8: Predicted trends in illness of sick leave versus ventilation rate.

Four of the curves are based on empirical studies, the particle concentration model curve uses a much simpler 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 applicable only 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 open plan offices and recirculation. At least one study (Jaakkola and Heinonen, 1995) shows that workers working alone in a room have less 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 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 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 possibly an effective alternative to increasing ventilation rate when it come to reducing absenteeism.

Milton et al. (2000) is the most important source for estimating the impact of ventilation on absenteeism in the Rehva Guide, because it concerns offices and the other sources concern barracks and a nursing home. Milton et al. (2000) not only found an effect of ventilation rate on absenteeism, but also of the use of a humidifier in the HVAC system and of working in an area with formally reported IEQ complaints.

The results of Milton et al. (2000) show 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 lower ventilation (12 l/s*person) compared to higher ventilation (24 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 with concomitant increase in BRS. More generally in can be stated that use of a humidifier increases absenteeism because it can be an indoor air pollution source. Then avoidance of several or all indoor air pollution sources may be more effective in reducing absenteeism than increasing the ventilation rate from approximately 12 to approximately 24 l/s*person.

Table 2: 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 a area *with formally registered indoor air complaints* on short-term absenteeism is of approximately the same size as the effect of lower ventilation compared to higher ventilation. Table 2 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 whether a formal complaint had been made to the corporate environmental health and safety office within the last three years.

Working in a complaint area increases only short term absenteeism. A plausible explanation of this result is as follows:

In general 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 complaints 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 leaves it leads to an increase of short-term absenteeism rather then 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 review 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 sickness absenteeism increases in *all* diagnose categories, and not only in those that are indoor air quality related. Workers who move in the other 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 2 support this view. It turns out that in building parts with a high level of indoor air complaints there is more short-term absenteeism but less long-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. 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 productivity (this paper). Loyalty will be especially decreased when it is a management decision to work in an open plan layout and workers would prefer cellular offices.

Discussion

The Rehva Guide states that it is its main purpose to establish quantitative relationships of indoor environmental aspects with productivity and absenteeism. Concerning the main quantitative relationships established (temperature with productivity, ventilation with productivity and ventilation with absenteeism) the publications on which these relations 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.

The purpose of this paper is to establish what in practice are, or probably are, the most effective measures to increase productivity and decrease absenteeism, given the total of the presently available evidence. Following this purpose we have come to the following conclusions:

Concerning the impact of temperature on productivity:

- The relationship presented in the Rehva Guide, where productivity is maximal at 21.75˚C, is only valid for air conditioned environments. In free running environments productivity is probably maximal at the matching comfort temperature, which can be 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, productivity will probably 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 productivity:

- Strict avoidance of indoor air pollution sources is more effective (a factor 10 or more) in raising productivity than increasing the ventilation rate above 10 l/s*person.
- Housing in small (two person) offices with occupant control of temperature is more effective (a factor 3 to 15 or more) in raising productivity 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 productivity and will have no negative side effects. Increasing the ventilation rate may result in lower productivity 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:

- For the time being the conclusion is that avoiding open plan offices and recirculation is possibly an effective alternative to increasing ventilation rate when it come to reducing absenteeism. More research and/or theoretical modelling are needed.
- Avoiding a typical indoor air pollution source like a humidifier is as 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 Leyten and Kurvers (2006) and Leyten, Kurvers and Van den Eijnde (2009) 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 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.
- 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 limiting external and internal heat load, using thermal effective building mass and offering the occupants adaptive opportunities.

Leyten and Kurvers (2006) and Leyten, Kurvers and van den Eijnde (2009) intend to show that robust measures, especially when combined, will bring much more occupant health and satisfaction than less robust measures. This paper intends to show that robust measures also contribute more to increasing productivity and reducing absenteeism than less robust measures.

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