Evaluating IAQ effects on people

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ABSTRACT
Following a comprehensive review of research over the 150-year history of mechanical ventilation, the recent European Multidisciplinary Scientific Consensus Meeting (EUROVEN) considered that only 20 studies relating ventilation (i.e. outside air supply rate per person) to human response were 'conclusive'. From them, a small number of conclusions were drawn, and some very large gaps in our knowledge of this important area of research were identified. Taking these as the starting point, this paper formulates a strategy for evaluating IAQ effects on people. It formulates some critical hypotheses and recommends appropriate research methodology for testing them. The first goal is to prove causation, the second is to identify the mechanisms of causation and the third is to assess the magnitude of the resulting positive or negative effects. Cross-sectional studies prove association, not causation, and it will thus be necessary to perform field intervention experiments. Economic, ethical and commercial considerations often make it impossible to perform the reversible interventions that are necessary to eliminate confounding. A neglected alternative is randomized scheduling of upgrades that would have been performed anyway. This powerful research strategy need not increase costs, is as ethically defensible as a clinical trial and will usually be commercially acceptable.

INDEX TERMS
Ventilation rate; Comfort; SBS; Productivity; Research strategy

INTRODUCTION
Ever since humans moved from trees to caves, taking with them a preference for fresh air, ventilation has been of central importance, not least because it accounts for an almost incredible 30–40% of all energy use. The more ventilation, the higher the energy cost, whether it is measured in terms of wood for the fire in the cave, coal for the hearth, oil for heating or electricity to turn the fan and run the compressor that cools the incoming outside air. Heat recovery can reduce some of this cost, but it might be thought that over the thousands of years of natural ventilation and the 150 years of mechanical ventilation mankind would long ago have been able to justify the cost of ventilation in terms of its benefits, so that the ventilation rate and the energy consumption it requires could be decided rationally. In fact, it is only in the last 10 years that any benefit at all has been proven. A meta-analysis by Mendell (1993) demonstrated that ventilation rates below 10 l/s/p can significantly aggravate health outcomes, and another by Seppänen *et al.* (1999) demonstrated that further increasing ventilation rate from 10 up to 20 l/s/p may further reduce the incidence and severity of SBS symptoms. Still more recently (Wargocki *et al.*, 2002), the European Multidisciplinary Scientific Consensus Meeting (EUROVEN) reviewed all available research on ventilation rates and concluded that only 20 studies were 'conclusive', i.e. provided sufficient information on ventilation, outcomes such as health effects, data processing and reporting. Taking these 20 studies and the EUROVEN consensus on

what they show as the starting point, the purpose of this paper is to set out a constructive strategy for near-future research to fill the gaps in our knowledge, formulating hypotheses that are capable of being disproved and in each case recommending a research methodology and approach that are capable of 'conclusively' testing them.

THE EUROVEN CONSENSUS

EUROVEN reviewed 105 relevant papers published in peer-reviewed journals before reaching a consensus on the 23 papers reporting 20 studies of ventilation rate that they considered to be 'conclusive', all listed in Table 4 in Wargocki *et al.* (2002). The consensus on ventilation rates can be briefly summarized in the following points:

1. Ventilation affects comfort, health and productivity.
2. Ventilation rates below 25 l/s/p in offices increase SBS and sick-leave and decrease productivity.
3. Air change rates above 0.5 h^{-1} in homes reduce HDM (House Dust Mite) infestation and may thus reduce the prevalence of allergies.
4. Pollution sources other than bioeffluents may require increased ventilation.
5. More information on the ventilation of schools and homes is required.

A further nine studies, including two of the above 23, all listed in Table 5 of the same paper, were found to be 'conclusive' and to provide evidence on how ventilation system type and cleanliness affected the same outcomes, leading to a consensus on the following two additional points:

6. The more complex the ventilation system the more there is to go wrong.
7. Poor design and maintenance of HVAC systems increases SBS.

COMMENTARY ON THE EUROVEN CONSENSUS

Minimum Ventilation Rate

The EUROVEN consensus does not endorse Mendell's (1993) conclusion that ventilation rates above10 l/s/p cannot be shown to be too low. On the contrary, Point 2 above moves the ventilation rate goalposts very considerably towards higher minimum ventilation rates, making it more imperative than ever to quantify the benefits that would accrue from the massive increase in energy use worldwide that this implies. Point 2 of the consensus, in stating that increased ventilation will lead to qualitatively better outcomes, does not provide the necessary quantitative justification for society to make a rational decision on the investment. The research approach proposed in this paper would provide the basis for a proper cost–benefit analysis of ventilation rate.

Maximum Ventilation Rate

The EUROVEN consensus considers the results reported by Jaakkola and Miettinen (1995) to be 'conclusive' but lists only its finding that the risk of SBS increased at ventilation rates below 15–25 l/s/p, omitting mention of the fact that the same paper reported that in the same study in the same buildings, the risk of SBS also increased at ventilation rates *above* 25 l/s/p, in comparison with 15–25 l/s/p. An increased risk was observed for all symptoms, and reached significance for eye symptoms, mucosal irritation and allergic reaction. Although this is an isolated result that did not form part of the EUROVEN consensus, the fact that the study was judged ‘conclusive’ means that a possible need for maximum ventilation rates should be investigated.

Health Risks Associated with Different Ventilation Systems

The EUROVEN consensus concludes that air conditioning systems, i.e. ventilation systems with full control of temperature and humidity, increase health risks (Point 6 above), citing Sundell *et al.* (1994) among other ‘conclusive’ studies as evidence, but omits to mention that in the same study, both naturally-ventilated and mechanically-ventilated buildings were associated with increased health risk for the occupants of 1-2 person offices. The odds ratio for these building types was 3.0. As all three types of system are widespread and will no doubt continue to be operated and installed in new buildings, the causal mechanisms behind these different health risks clearly require further systematic investigation.

Study Design

Only three of the 23 papers listed by EUROVEN as providing ‘conclusive’ information on how ventilation rates affect people (Table 4 in Wargocki *et al.*, 2002) were classified as reporting ‘experiments’ (Jaakkola *et al.*, 1991; Menzies *et al.*, 1993; Wargocki *et al.*, 2000). The remainder were listed as ‘cross-sectional’ or ‘case–control’ studies. In fact, three more of the 20 studies can also be classified as ‘experiments’ in which the effect of an intervention was observed: Fanger (1988), listed by EUROVEN as a cross-sectional study, used an external panel to assess perceived air quality in a hall with and without occupants; Smedje and Norbäck (2000), also listed as a cross-sectional study, applied an SBS questionnaire before and after classroom upgrades had been carried out; and Warner *et al.* (2000), listed as a case–control study, randomly assigned households to the four conditions of a 2 × 2 design (to have mechanical ventilation installed or not, and to be provided with a high efficiency vacuum cleaner or not). In all six studies, outcome variables with and without an intervention were compared.

Case–control studies compare the conditions experienced by patients and controls, with no intervention. Cross-sectional studies focus on associations between independent and outcome variables, the data being acquired passively, without intervention. Confounding between variables means that neither case–control nor cross-sectional studies can prove causation, as associations with additional measured or unmeasured factors can always provide plausible alternative explanations of the results. For example, even if children with bronchial obstruction are more likely than their healthy controls to live in dwellings with dampness problems, as shown by Øie *et al.* (1999), both postulated cause and medically diagnosed effect may be due to poor household economy, which clearly may make it economically unfeasible to move to better accommodation while also exposing the child to the increased health risk of a relatively impoverished lifestyle. Only properly designed intervention experiments can break such an association. When proof of causality is required, as it is when an increase in ventilation rate that implies such large investments and so much more energy use is proposed, an experimental approach must be used to provide proper justification.

Remaining Gaps in Knowledge

EUROVEN considers it to be proven that ventilation affects comfort, health, and productivity, and that ventilation rates below 25 l/s/p have negative effects on health, but aside from HDM infestation in dwellings, we do not know the mechanisms of these effects, which air pollutants cause them or the critical levels of those pollutants. In other words, research in this area is still wide open, and although there is now a consensus that ventilation matters, we need to know how much more is required, who this would benefit, and how much. If we understood the mechanisms by which poor ventilation has negative effects on people, we would be better able to suggest new solutions to the basic problem, which is that providing much more ventilation than we do today would consume a prohibitive amount of energy.

DESCRIBING IAQ

Two sets of metrics are used to characterize IAQ:

1. Measurement on the dimensions on which an intervention can change IAQ. For example, temperature, air velocity, water content in g/kg dry air, $\mu g/m^3$ of a given pollutant.
2. Measurement on the outcome dimensions that are affected by IAQ. For example, perceived air quality, acceptability, percentage dissatisfied, SBS symptom intensity, skin dryness, nasal peak flow, sick leave, productivity, mortality.

It is important to realize that although the physical and chemical metrics listed as Type 1 can always be measured, the values can only be characterized as indicating ‘good’ or ‘bad’ IAQ by reference to standards that are defined in terms of the Type 2 metrics. Although it is true that in the case of a pollutant known to be toxic or irritant at some level, a decrease in concentration may be characterized as better than an increase in concentration, this is not a sufficient justification if the intervention causing this to happen is expensive in terms of energy or investment—the improvement might be so small as to be imperceptible or negligible in terms of the Type 2 outcomes it is supposed to improve. Thus, while the primary goal of IAQ research is to show that a given change in one or more Type 1 metrics has an effect on one or more Type 2 metrics that could not have occurred by chance, the value of this information in practice is very limited unless the dose–response relationship is also quantified. Only then can cost–benefit analysis be used to justify the proposed intervention. Even in the case of airborne carcinogens, whose outcome is death or serious illness for a small proportion of those exposed, it is now insufficient to show that they are indeed carcinogens and present in indoor air—there are so many pollutants with potentially serious outcomes that a proposed intervention must usually be justified by quantifying the reduction in risk that would result and showing that it would pay in national economic terms.

NEW EXPERIMENTAL METHODOLOGY IN THE FIELD

New methodology is required to be able to prove causality in field experiments without making it impossible to obtain the necessary funding or access to buildings. An approach not represented in the papers selected by EUROVEN might be termed ‘Randomly Scheduled Upgrades’ (RSU): when an administrative decision has been taken to upgrade a number of comparable building units, such as classrooms, schools or office buildings, the before/after measurements of outcome criteria (e.g. as in the study reported by Smedje and Norbäck (2000) will usually be confounded with other factors, e.g. when the dilapidation of the buildings determines the order in which they are upgraded, it is confounded with calendar time, making it difficult to prove causality. This and all other conceivable confounding can be broken by randomly scheduling the upgrades. This simple expedient is cost-neutral and is therefore an economically feasible way of performing what amounts to a rigorous field intervention experiment that would be prohibitively expensive and difficult to arrange if undertaken for purely scientific purposes. The difficulty is administrative, in that researchers must work closely with decision makers, sometimes even with politicians, before upgrades are funded and scheduled, instead of asking for access after the administrative decisions have been taken.

RESEARCH ON MULTIPLE IEQ FACTORS

An important research goal is the development of a standard means of making an integrated assessment of multiple indoor environmental factors. This goal has already been addressed in various ways by researchers now working at ICIEE, in experiments in which two or more indoor environmental factors have been the independent variables in human experiments carried out under controlled conditions. The dependent variables in these experiments have been SBS symptom intensity (health), questionnaire responses (subjective assessments of comfort, acceptability and annoyance), and the objectively measured performance of simulated work (tasks assessing the component skills required for productivity). These studies give the general impression that while there is little or no interaction between such factors as noise, air quality and temperature in terms of subjectively assessed acceptability, so that annoyance from multiple sources appears to be additive, there can be quite large interactions in terms of how they affect performance, noise sometimes counteracting the effects of moderate heat stress on office work, while bright lighting and visual information overload sometimes makes make them worse.

A theoretical interpretation in terms of passive environmental effects on arousal does not account for all of these effects unless concurrent environmental effects on motivation and effort are also assumed to be taking place in the experiments. In recent ICIEE experiments in the field laboratory the metabolic rate of groups of subjects can be estimated from measured CO_2 values. There are indications that the presence of indoor air pollution tends to reduce metabolic rate while moderate heat stress increases it (e.g. Wargocki *et al.*, 2000). Early work on moderate heat stress assumed that performance was reduced because arousal was consciously or unconsciously reduced, so as to reduce the rate of metabolic heat production and thus avoid or postpone sweating. Although this is still the most plausible explanation of what occurs in practice and in experiments in which subjects exert a realistically low level of effort, it is necessary to assume that conscious effort may be exerted by well-motivated subjects to maintain performance, reversing the passive environmental effects that would otherwise be expected. There may also be direct effects of temperature on metabolic heat production, even at low levels of heat stress. Thus, in spite of repeated attempts to address experimentally and theoretically the integrated assessment of multiple indoor environmental factors, a great deal more laboratory research remains to be done before design and operational criteria can usefully be based on an understanding of the underlying mechanisms.

FIELD METHODOLOGY

The following dependent variables could be used in the field in making an integrated assessment of multiple indoor environmental factors, in the categories of health, comfort and productivity:

Health
1. Sick-leave records
2. Recorded visits to company clinic or nurse
3. Absenteeism records
4. Complaints log maintained by building maintenance service
5. Retrospective SBS questionnaires on symptom frequency
6. Visual–Analogue scales of SBS symptom intensity 'right now'

Comfort
7. DTU split-scales of overall acceptability
8. Occupant Satisfaction Survey over Internet (www.cbe.berkeley.edu)

Performance
9. Call-centre records of talk-time and call handling time
10. Automated queue records of customer processing time
11. Insurance company claims processing time records
12. Records of school examination results
13. Standard tests applied in classroom (embedded tasks)
14. Hospital records of recovery time and medication following surgery
15. Retail sales

In all of the above, the measured outcome variable is goal-related—good health, occupant satisfaction, acceptability, rapid customer service, school achievement, rapid convalescence, reduced painkilling and therapeutic medication and increased retail sales are the underlying goals of building design and operation in each field of human activity. These dependent variables are also at a sufficient distance on the causal chain from the specific effects of any given indoor environmental factor to be capable of integrating the effects of the necessarily very diverse mechanisms by which different indoor environmental factors may be expected to affect the occupants of buildings.

FIELD STUDIES

It is useful to distinguish between two main types of field study—passive epidemiological surveys and intervention experiments. In the former, nothing is changed but a large number of possibly relevant independent variables are measured. In the latter, only one or two environmental factors at a time are changed and the effect of uncontrolled changes in all other factors on the dependent variables measured is assumed to average to zero. On the Null Hypothesis of no effect of the variables being manipulated the probability of occurrence of the observed results can then be calculated on the basis that all observations are simply random samples of what would normally have been observed without an intervention. The three main advantages of an intervention experiment over a passive survey are that: (1) confounding between variables is eliminated, making it possible to prove causation rather than association; (2) far fewer measurements need be taken—just those required to document that the intended intervention was successful; and (3) far fewer assumptions about level of measurement and the underlying population distribution are required than in using advanced mathematical methods capable of handling covariation to analyse the data obtained in passive epidemiological surveys. However, epidemiological surveys are a very useful means of documenting the real-life combinations and ranges of indoor environmental conditions to which people are exposed and of generating hypotheses about causative mechanisms that can subsequently be tested experimentally in the laboratory or by means of intervention experiments in the field. All of the outcome variables proposed above could be used in either type of field study.

Passive Epidemiological Surveys

For the purpose of examining the effects of multiple IEQ factors, a cross-sectional approach is more appropriate than a longitudinal one, comparing outcome variables across many similar buildings in the same category rather than comparing successive occasions in a reduced set of buildings, as in the latter case seasonal variation will dominate and there will be confounding with sociological driving factors that vary with the seasons. In the former case the buildings can be selected because they offer a wide range of conditions and combinations of conditions within a given season, such as the heating season. Clearly, schools should be compared with schools, offices with offices and hospitals with hospitals, but within these building categories different architectural and engineering approaches are certain to provide the required diversity of indoor environmental conditions. Data from dozens or even scores of buildings will be required, and obtaining sufficiently representative measurements of all the possibly relevant independent variables will be a major expense. ICIEE is currently using this approach in an exploratory study of the health consequences of living in damp buildings.

Field Intervention Experiments

Interactions between indoor environmental factors can usefully be studied in a single building, although it may be necessary to use several buildings in order to be able to manipulate experimentally all of the factors of interest. A 2 × 2 experiment is a robust unit for investigating interactions between factors, and a week is a very suitable duration for each combination of conditions, not only because the intervention of a weekend is inevitable and provides a fresh and comparable start for each exposure, but also because symptoms of ill health or fatigue may take several days to develop and an adaptive approach to individual or group work that is itself a consequence of environmental changes involves a learning process that may extend over several days. Building occupants should be blind to the interventions as far as possible, and in order to avoid chance confounding of conditions with uncontrolled external factors such as weather, a crossover design with parallel groups on different floors or in different parts of the same building should be adopted. Where this is not possible, the basic 2 × 2 unit of the design should be repeated a number of times to reduce the probability of chance confounding. ICIEE has used this approach successfully in the past and is currently engaged in several field experiments of this kind.

Statistical Analysis

The primary goal is to determine whether the environmental factors included in either kind of study have any statistically significant effect at all on the dependent variable concerned, and whether any observed interaction between two or more factors is significant. Documenting the ranges that occur in practice and their association with other environmental factors is clearly irrelevant if the analysis indicates that the observed results could have occurred by chance. If significant main effects or interactions can be shown, the second goal is to determine the size of the effect, in order to be able to determine whether they have any practical significance and to motivate the investment that would be required to optimize conditions. Both statistical and practical significance can thus be determined in the first instance from intervention experiments in which only two levels of each factor have been imposed. Only the third goal, which is to determine the approximate shape of the dose–response relationship, requires one or more additional levels of each factor. While passive epidemiological surveys are capable of addressing the first and second goal, it is seldom possible to usefully address this third goal using passive survey data.

Environmental Variables

Building design and operation both affect the following environmental variables and there is reason to believe that they are likely to interact with each other in terms of their effects on most of the proposed outcome variables:

1. Room temperature
2. Relative humidity of room air
3. Outside air supply rate per occupant
4. Nature and source strength of air pollution sources
5. Resulting levels of specific air pollutants
6. Resulting levels of ozone in room air
7. Nature, number and size distribution of airborne particulate matter
8. Amount of dust currently retained by supply air filters
9. Surface dust contamination levels
10. Quantity and nature of allergenic material in room air and on surfaces
11. Background noise level from ventilation or traffic
12. Noise distraction source strength, especially intelligible speech
13. Lighting level and distribution
14. Daylight (relative intensity and diurnal variation)
15. Availability and nature of view-out
16. Visual and acoustic privacy (view-in and risk of being overheard)
17. Occupancy level (number of occupants per 100 m^2)

In certain cases, there will also be well-understood and often fairly trivial physical and chemical interactions between two or more of these environmental factors, e.g. temperature and pollution emission rates, ozone and VOCs, outside air supply rate and the resulting concentration of air pollutants, occupancy level and privacy, daylight and view-out, etc. These should be taken into account in the design and analysis of the experiments.

TESTING HYPOTHESES

Research to describe and quantify IAQ effects on people must advance by testing falsifiable hypotheses. The following hypotheses formulate what we urgently need to know *next* in this field:

1. Negative effects on health, including effects on pre-clinical symptoms such as SBS, can occur even when conditions are not perceived as differing from the optimum.
2. Long-term exposure to conditions that can be shown to cause pre-clinical symptoms will eventually cause chronic illness in sensitive individuals.

3. Negative indoor environmental effects on health, comfort and productivity can occur even if no single pollutant that can be shown to be present exceeds current toxicological limit values.
4. The level of annoyance caused by the departure from optimum levels of such unrelated and independent factors of the indoor environment as temperature, air pollutant levels, lighting and noise is, to a first approximation, additive.
5. Analogous environmental effects on different aspects of overt behaviour, including the work that contributes to productivity, are not necessarily additive and may even be in opposing directions.
6. Productivity is more affected by large environmental effects on the health of a small minority of sensitive occupants than by small environmental effects on the vast majority of occupants.
7. Providing individual control of one or more indoor environmental factors will always have a beneficial effect on health, comfort and productivity.
8. Dust depots in contact with indoor air, including those present in particle filters in the supply or return air, on floors, in textiles, inside office machinery, furniture and open shelves, can by a process of adsorption, chemical conversion and re-emission constitute an important source of the chemical pollutants that load indoor air.
9. Negative indoor environmental effects on SBS and productivity can be caused by the mechanism of involuntary behavioural response, such as hypoventilation causing lowered metabolism, increased intra-cranial pressure, headache and a reduced ability to concentrate, a protective increase in blinkrate that progressively obscures vision and slows the rate of visual data acquisition, or lowered arousal that adaptively reduces metabolic heat production in response to moderate heat stress.
10. Negative indoor environmental effects on productivity can be caused by the mechanism of voluntary behavioural response, such as avoidance behaviour, leading to reduced time on task, or reduced motivation, leading to reduced workrate or accuracy.

These hypotheses should be validated or refuted in as many different contexts as possible, from schools to workplaces. Although they can conveniently be addressed in the laboratory, field experiments are required if the findings are to be used in practice.

PRACTICAL IMPLICATIONS

If any of the above hypotheses should prove to be true, the finding would have far-reaching and hard-hitting practical implications. Liability litigation would increase if H1, H2 or H3 were validated. Architects would be able to compensate for one factor by improving another if H4 were validated, but would not be as free to do so if H5 were also validated. Indoor environmental standards based on group average effects would have to be revised if H6 were validated, for example, by specifying the degree of individual control that must be provided, especially if H7 were shown to be true. The design of HVAC systems and interiors would have to be radically changed if H8 were validated. If particle filters were demonstrated in the course of validating H8 to be a relatively major contributor of the pollutants present in indoor air, new ways of removing particles from supply air that do not allow them to accumulate while remaining in contact with the supply or room air would be urgently required. If H9 or H10 were validated we should know much more about the mechanisms by which indoor air has negative effects on people and we would be able to formulate new hypotheses that tested alternative counter-measures. There is still a great deal to be done.

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