WS 1 RESEARCH NEEDS AND APPROACHES PERTAINING TO THE INDOOR CLIMATE AND PRODUCTIVITY

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BACKGROUND

The indoor environment affects the health, comfort and performance of occupants. All three are important, but the cost of improved design, operation, maintenance and energy use in buildings must usually be justified in terms of the expected effects on productivity. While there is no doubt that effects on health, comfort and performance translate into effects on productivity, there is an urgent need to discover which of the hypothesised mechanisms of cause and effect are valid, to quantify how much each mechanism affects productivity in different work situations, and to validate predictions in the field.

AIM AND SCOPE

The objectives of this workshop are to define and prioritise a set of specific research needs concerning the effects of indoor environmental conditions in non-industrial buildings on productivity, to characterise and recommend alternative research approaches, and to prepare a taxonomy of productivity metrics and their suitability for different purposes. The economic concept of productivity will be taken here to include the added value provided to society by non-profit schools and hospitals.

STATE OF THE ART REVIEW

Economical aspects

Fisk et al. (1997, 1998) have estimated that in the USA the yearly potential gain of productivity increase due to reduction of respiratory infection cases equals to 6-14 billion USD, due to reduction of allergy and asthma cases 2-4 billion USD, due to reduction of sick building syndromes 15-38 billion USD, and due to improved working efficiency 20-200 billion USD.

Seppänen (1999) has estimated that the total annual cost of poor indoor climate in Finland is about 2.7 billion Euros.

Wyon (1996) has reviewed published analyses showing that "cost-benefit analyses that assume an impact on overall productivity of as little as 0.5 % have shown that the payback time for a general upgrading of currently unhealthy office buildings, defined so as to include about 40 % of the building stock, would be as low as 1.6 years."

Mudarri (1999) has stated that there is a need for public policies that "include the establishment of protocols of good building practices; a rational integration of energy and indoor environmental policies; a guidance and software packages for building owners and others that assist in calculating bottom-line impacts of indoor environmental quality projects."

Dorgan et al. (1999) have stated that "the productivity benefits related to IAQ are an employee health issue" and that "further research is required including:
- research studies to investigate fully the causal relationship between the indoor air quality of commercial buildings and hypersensitive pneumonitis (HP) and occupational asthma (OA)
- a set of guidelines to perform productivity studies and benchmark existing buildings properly
- case studies to determine the actual health and productivity benefits that result from improved indoor air quality due to the implementation of HVAC improvement measures."

Productivity and performance of workers in controlled conditions

In simulated office work an extra pollution load, which was a 20-year old used carpet, increased the percentage of dissatisfied from 15 % to 22 %, increased the prevalence of sick building syndromes, and decreased the amount of typing by 6,5 %, Wargocki et al. (1999).

In computer-based neurobehavioral tests modest correlations between higher temperature, lower humidity, and lower air velocity, and lower test results have been observed, Nunes (1993).

Productivity and performance of workers in field studies

The direct measurement of productivity is the ratio of output to the input used to produce the output. Field studies have been conducted in real production environments with the research frames of "intervention" and "case-control". Most of the recently reported studies are conducted in office type workplaces.

Lorsch (1994) has described the results of three large studies of office worker productivity involving almost 6000 employees in the USA. Lorsch has concluded that "while there is a preponderance of opinion that improving the work environment leads to higher productivity, quantitative proof of this statement is sparse and controversy. A minority believes that influences outside the workplace primarily determine productivity. Claims of increased productivity due to improved environmental conditions are usually based on surveys, questionnaires, interviews, self- evaluations, and other qualitative measures. Few data exist to evaluate this effect quantitatively. Among the items that affect office-worker productivity, HVAC and IAQ are rated well below such items as privacy, interpersonal communications and relationships, office arrangements, and managerial attention."

The studies in industrial workplaces have mostly covered the influence of very high and very low indoor air temperatures on labour productivity, and accident rates in industrial work. Many of the studies date from former decades. Clements-Croome at al. (1995) have concluded: "research is needed in the following areas

- The meaning of comfort and differences between comfortable, acceptable, preferable and tolerable thermal environments.
- The link between productivity, well-being and comfort or discomfort.
- The relationship between thermal comfort and other design requirements such as air quality, noise and light.
- Optimal design and the relationship between temperature, economics, health, productivity, energy use and comfort."

Boyce (1989) has reviewed a number of case studies of the direct effects of lighting conditions on task performance both in industrial and office type workplaces. Variables used are the illuminance, illuminance uniformity, luminance, glare, the colour properties of the light sources and the presence of flicker. Performance is measured in terms of speed or accuracy of production or indirectly in terms of fatigue, absenteeism rate and the incidence of complaints. Boyce has concluded: "case studies tend to have a low degree of experimental control compared to laboratory studies."

As indirect measurement of productivity, the following productivity measures have been recommended in ASHRAE Workshop "Indoor Quality" in Baltimore September 1992 as being significant:

- absence from work, or workstation
- health costs including sick leave, accidents and injuries
- interruptions to work
- controlled independent judgements of work quality
- self-assessments of productivity
- speed and accuracy of work
- output from pre-existing work groups
- cost for the product of service
- exchanging output in response to graded reward
- volunteer overtime
- cycle time from initiation to completion of process
- multiple measures at all organisational levels
- visual measures of performance, health and well-being at work
- development of measures and patterns of change over time.

Clements-Croome (1999) has concluded that "a good working environment will help to provide the user with a good sense of well-being, inspiration and comfort. The main advantage of good environments is in terms of reduced upgrading investment, reduced sickness absence, an optimum level of productivity and improved comfort levels. Individuals respond very differently to their environments and the research supports the correlation between worker productivity, well-being and environmental comfort."

Levin (1995) has reviewed that the body's response to its environment is an integration of responses to the separate indoor air quality factors, and there are many possible outcomes of combined or multiple exposures. The combined effects of the thermal environment may be more important than acoustics, lighting and air quality.

Wyon (1996) has shown that individual control equivalent to ± 2 °K would satisfy more than 90% of the employees and ± 3 °K would satisfy 99 % of the employees, and concluded following a review of the literature that "published experimental data indicate that conventionally acceptable indoor working environments may be affecting human

performance by various mechanisms by as much as 5 % to 15 %." The review distinguished between six types of productivity metrics, and cited published work in which each of them had been used:

1. Simulated work - subject performs a realistic but artificial task
2. Diagnostic tests - subject performs a test procedure unlike any real task
3. Embedded tasks - outcome metric derived from part of an existing task
4. Existing measures - existing outcome metrics are made available
5. Absenteeism - new or existing records of sick leave are used
6. Self-estimates - subjects are asked to report their own perceived level of efficiency

In addition, a new approach to productivity research was introduced, as follows:

"A new approach would be to formulate specific mechanisms to explain exactly and in detail just how a given change in office layout or environmental conditions might be expected to affect individual performance. Each mechanism should be defined by postulating a chain of falsifiable hypotheses, each of which must be true for the mechanism to be valid. A key concept in this approach is that of the intervening variables, the outcome metrics for one hypothesis which become the independent or driving variables for the next link in the chain. It is then possible to devise experiments to test each link in the chain separately, usually by very different means: the intervening variables may relate to the group or to an individual, and may be indices of health, mood, motivation, comfort, behaviour or even performance - individual performance is an important intervening variable between IEQ and the productivity of the group. Part of the economy of this approach lies in the fact that not all of the hypotheses in a chain may need to be tested, as the chain is invalidated if any one of the hypotheses proves to be untrue. (Note that) there may be several alternative routes between cause and effect, involving different chains of hypotheses."

USE OF THE ABOVE APPROACH

Specific mechanisms by which alternative workplace designs or alternative modes of operation may reasonably be claimed to affect productivity are expressed as sets of linked hypotheses. Hypotheses can then be tested one by one. The necessary experiments involve a wide variety of outcome metrics, but the crucial point is that the hypotheses are falsifiable - they are either true or untrue, and experiments can be devised to determine which is the case. If any one of a particular chain of hypotheses is shown to be untrue, the mechanism described by the chain is not valid. By disassembling the usually vague and general claims about architectural and HVAC design into the constituent parts of the mechanisms by which they are claimed to act on productivity, the claims can be either validated or disproved. Different aspects of workplace design and operation can be quantitatively compared in terms of their relative effects on the intervening and outcome variables.

TASKS PERFORMED DURING WORKSHOP

Task 1: Productivity metrics

Workshop participants developed a list of productivity metrics and, via voting, each participant selected the three metrics most valuable for productivity research. As a basis for

the selection of priority metrics, participants were asked to consider the relevance of the metrics for productivity, the difficulty in collecting data on metric value, and the number of opportunities for using the metric.

Task 2: Independent variables

A list of indoor environmental independent variables expected to affect productivity was developed. Each workshop participant voted for the three independent variables that, in their opinion, should be considered priority independent variables in productivity research

Task 3. Overall study design

A general set of study designs was developed and each workshop participant voted for the two study designs they considered most valuable.

Task 4. Work or activity types

Workshop participants listed the types of work or the activity for which productivity research is needed and identified their priorities via voting. Each participant had three votes.

Task 5. Blinding and Control/Reference Groups

Via votes, participants indicated their views about the importance of conducting studies blindly and of including control/reference groups in intervention studies.

RESULTS

The prioritisation (high, medium and low) was assigned by the workshop chairs based on the votes.

Table 1. Results of task 1: Productivity metrics

Productivity metrics	**Number of votes**	**Percentage**	**Priority**
Existing company measures	20	61 %	High
Break time/ voluntary overtime/ punctuality	16	48 %	High
Staff estimates	11	33 %	High
Simulated work	11	33 %	High
Absenteeism	10	30 %	High
Diagnostic tests	5	15 %	Medium
Embedded tasks	5	15 %	Medium
Physiological measures	5	15 %	Medium
Peer/ supervisor estimates	1	3 %	Low
Management load/ complaints	1	3 %	Low
Staff turnover	0		Low

Table 2. Results of task 2: Independent variables

Independent variable	Number of votes	Percentage	Priority
Ventilation rate	25	76 %	High
Temperature	18	55 %	High
Noise level	9	27 %	Medium
Particle concentration	7	21 %	Medium
Personal control of physical environment	6	18 %	Medium
Air movement	6	18 %	Medium
Amount of daylight	4	12%	Medium
Thermal discomfort	3	9 %	Low
HVAC maintenance and cleaning	3	9 %	Low
Quality of cleaning	2	6 %	Low
Volatile organic compounds (VOCs)	2	6 %	Low
Quality of lighting	2	6 %	Low
Quality of noise	2	6 %	Low
Odour	1	3 %	Low
Quantity of lighting	0		Low
Privacy	0		Low

Table 3. Results of task 3: Overall study design

Overall study design	Number of votes	Percentage	Priority
Intervention field study	30	91 %	High
Laboratory experiments	27	82 %	High
Observational longitudinal natural experiment	6	18 %	Medium
Observational cross sectional field study	4	12 %	Medium

Table 4. Results of task 4: Work or activity types

Work or activity type	Number of votes	Percentage	Priority
Offices	30	91 %	High
Schools	29	88 %	High
Health care	17	52 %	High
Light industry	7	21 %	Medium
Call centre	5	15 %	Medium
Retail	2	6 %	Low
Clean rooms	1	3 %	Low
Heavy industry	0		Low

Table 5. Results of task 5: Blinding and Control/Reference Groups

Reference	Number of votes	Percentage
Blinding or placebo	21	64 %
Control groups	11	33 %

SUMMARY

Workshop participants endorsed the use of a variety of productivity metrics. It is worth noting that all of the high priority metrics could be used in field experiments in real workplaces, while only two of them could be used in laboratory experiments. There was a clear endorsement of the current focus on air change rates and temperature as the most important indoor environmental factor for productivity research, with particle concentration, personal control and air movement receiving significant support. Experimental studies in the field and laboratory were clearly preferred over observational studies. Productivity research in offices, schools and health care facilities was accorded the highest priority. Working conditions in heavy industry received no votes but this was probably because very few workshop participants were involved in this field. Blinding and placebo approaches were considered important, as was the inclusion of control groups in intervention studies.

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