CORRELATION BETWEEN INDOOR ENVIRONMENTAL QUALITY AND PRODUCTIVITY IN BUILDINGS

Prof. Dr. Ossama A. Abdou  
President, Center for Building Environmental Studies and Testing (C-BEST), Cairo, Egypt  
oabdou@hotmail.com

Dr. Gamal M. El.Kholy  
Associate Professor, Dept. of Architecture, Faculty of Engineering, Ain Shams University, Cairo  
gme1957@hotmail.com

Dr. Amal A. Abdou  
Associate Professor, Dept. of Architecture, Faculty of Fine Arts, Helwan University, Cairo  
molly_abdou@hotmail.com

Abstract

This paper consists of a collection of available information on qualitative relations between indoor air environment and worker productivity. While qualitative information is fairly plentiful, quantitative information is quite limited; and what is there, is highly controversial. Some researchers have published measured improvements in productivity of 2.8% to 9.5% due to improved environmental conditions; others claim productivity increases of up to 15%. On the other hand, many people maintain that the measurable changes in productivity are too small and too random to be caused by the indoor environment. While there is no proof that maximum comfort leads to maximum productivity, an improved environment decreases worker complaints and absenteeism. It appears, however, that other factors such as labor-management relations, interaction between workers, and the physical arrangement of their work spaces are far more important to worker productivity than the indoor air quality (IAQ). It seems that when workers have control over their environment, they tend to be more satisfied. When their environment is improved either through management initiatives or as a result of worker complaints, they take it as an indication that management cares for them, and it increases their job satisfaction, which indirectly may increase their productivity.

Most studies show that better lighting increases productivity and that working conditions are generally better when windows are provided. Other indoor environmental factors such as acoustics, thermal and olfactory aspects as well as humidity levels and ventilations rates seem to have correlations to worker performance as measured by factory outputs and industrial accidents, all of which are measures of productivity.

Indoor environmental quality (IEQ) is important to the health, comfort, and well being of building occupants. It is believed that poor IAQ is associated with a number of different phenomena, most notably, the Sick Building Syndrome (SBS), Building-related Illness (BRI), and Multiple Chemical Sensitivity (MCS), which, of course, have major effects on productivity. And, since that cost of providing the indoor environment is more than an order of magnitude smaller than the cost of the workers in that place, providing a superior environment may well be the most cost-effective way of increasing worker productivity.

Keywords: Indoor Air Quality, Indoor Environmental Quality, Productivity, Comfort
Introduction

A primary goal in building design is to design spaces that are conducive to the tasks being performed in these spaces and to operate building systems in an efficient manner. Building effectiveness is not a question of assessing whether standards have been met, but whether, in fact, actual building performance sustains reasonable occupancy and use in terms of individual and organizational well-being, health and productivity (Drake et al. 1986). When the building systems that regulate and control indoor environmental conditions do not function properly, not only does indoor air quality (IAQ) deteriorate, but also energy is wasted. Poor building performance may be the result of a conflict in performance requirements between several attributes, such as ventilation, lighting, or temperature. The cumulative effect of less than satisfactory performance culminates in "environmental stresses" perceived by the occupants.

Considering the great importance of the workplace, and the stresses related to it, it is surprising that researchers have, for the most part, ignored the effects of building indoor environment on productivity and job satisfaction. Early studies were field studies, usually carried out by industrial organizations to determine the effects of extreme temperature and humidity conditions on workers. In many more recent case studies occupants have been highly dissatisfied with an environmental attribute even though some of the technical measurements indicate that current standards are being met. Therefore, rather than dismissing occupants' concerns. This highlights the need to reassess the measurements and standards as they apply to more specific and newly emerging functional requirements.

Effect Of Poor Indoor Air Quality

In dealing with IAQ, a major goal is to characterize and understand the risks to human health which indoor pollutants pose. IAQ has become a concern, because indoor pollutant levels frequently exceed outdoor levels, and individuals may spend up to 90% or more of their time indoors. The potentially most hazardous indoor pollutants include radon, asbestos, inorganics, environmental tobacco smoke (ETS), organics, biologicals and non-ionizing radiation, the latter four primarily affecting productivity. Some pollutants, e.g., bacteria, viruses and carcinogens, directly affect the health of the occupants while others, e.g., odors and dusts, can cause significant discomfort, feelings of unpleasantness, disgust and distaste among workers, thereby leading to lower productivity. According to Grandjean (1980), air quality can affect job and environmental satisfaction.

Few data exist on the productivity lost because of poor IAQ. However, a number of surveys have been conducted, the most significant of which were those administered by a "building controls" company (Honeywell Technologies 1985) and a coalition of employee unions in New England, USA (EPA 1989). The 1985 survey found that approximately one in five (19%) of the 600 office worker respondents often or sometimes had difficulty doing their work because of office air quality. Eleven percent of all respondents reported that a 'tired/sleepy feeling' was a serious problem because of office air. Similarly, 9% of all respondents cited a 'congested nose,' 8% cited eye irritation,' and another 8% cited 'difficulty breathing' as being serious. This one-employee-in-five dissatisfaction ratio is rather significant. According to Woods (1989),"we could increase the productivity of 20% of our work force" simply by improving the air quality of most offices. He was further quoted as saying that "on average, we find that air contamination level indoors is between four and ten times higher than what you find outdoors." The problems are not new, but a change in building design has occurred. After the energy crunch of the 1970s, many property managers sought energy efficiency by tightly sealing their buildings. As a result, indoor pollution became aggravated by what is termed "Tight Building Syndrome." When maximum energy efficiency is the main goal, employee comfort and outside ventilation are often sacrificed.
The New England survey, which encompassed 94 state government office buildings, reported large numbers of complaints about health symptoms that respondents attributed to poor air quality: 30% reported having headaches, 44% reported fatigue or drowsiness, 37% reported eye strain, and 69% reported some loss in productivity on a daily or weekly basis due to poor IAQ. A part of the New England study included estimating the economic costs from medical visits, sick days lost and productivity losses. The results show that an average of 0.24 doctor visits per worker per year were attributable to poor IAQ.

A British study (Wilson and Hedge 1987) reported prevalence rates of work-related symptoms confirming those reflected by the New England survey. Likewise, in a major study on Danish Town Halls (Skov and Valbjorn 1987), similar prevalence rates of work-related symptoms were reported, thereby indicating that the concern is rather global and not limited to any geographic location.

To address office worker perceptions of IAQ effects on their comfort, well-being and performance, a stratified random sample of 600 office workers was surveyed (Woods et al. 1987). A significant percentage of respondents (39%) indicated that air quality is a "very serious" or "somewhat serious" problem, and 24% of the respondents were specifically dissatisfied with the air quality at the office. Moreover, 20% perceived their performance to be hampered by air quality. The symptoms they described are similar to those identified with Sick Building Syndrome (SBS). In the survey, workers in open office areas were one-and-a-half times as likely to report poor air quality and to say it affected their productivity than those who worked in enclosed or semi-enclosed offices.

The survey further found that workers in buildings more than 20 years old were one-and-a-half times as likely to complain of poor indoor air quality and to say that it hampered their work than workers in buildings less than 10 years old. Table 1 summarizes the respondents' perceived dissatisfaction with the relationship between age of building and IAQ. It further depicts the percentage of workers perceiving air quality as hindering their productivity.

Table 1. Dissatisfaction With Respect To Age Of The Building And Indoor Air Quality

<table>
<thead>
<tr>
<th>%-age of dissatisfied workers</th>
<th>Age of building (years)</th>
<th>%-age of workers perceiving hindered productivity</th>
</tr>
</thead>
<tbody>
<tr>
<td>19 %</td>
<td>&lt; 10</td>
<td>15 %</td>
</tr>
<tr>
<td>23 %</td>
<td>11&gt; – 10</td>
<td>20 %</td>
</tr>
<tr>
<td>29 %</td>
<td>20</td>
<td>23 %</td>
</tr>
</tbody>
</table>

Another outcome of the survey is the relationship between perceived indoor air quality and the existence of windows. If there were windows in the workplace, 21% of the workers were dissatisfied with air quality. If there were no windows, 29% were dissatisfied. Air quality was perceived to impede work by approximately 17% of those in building spaces with windows and 23% in work spaces without windows. In buildings whose windows were opened often the percent of workers indicating dissatisfaction with the air quality was 18%, if they were rarely opened 20%, and if they could not be opened 30%. No correlation was apparent between open windows and productivity. The percent of workers who perceived air quality to have an adverse effect on their work was 20% if windows were opened often, 15% if they were rarely opened, and 18% if windows were opened often, 15% if they were rarely opened, and 18% if windows could not be opened.

In an article on office pollution, Dubbs (1990) refers to studies that show that as much as 50% of employee absenteeism is due to upper respiratory infections, some of which can result from indoor air pollution. Evans and Jacobs (1981) state that air pollution or the perception that it exists can create stress among employees who believe that it poses threat to their health. The stress may be particularly intense among people who believe they have no control over the pollution. In addition to affecting workers' health and productivity, contaminants in building air can harm workers' morale (LaBar 1992).

According recent and ongoing research, allergenic fungi, dust, low relative humidity, bacteria, and chemical off-gassing from building materials, carpeting and furniture are among the most common causes
of IAQ problems. The pollutants remain in the air due to poor maintenance, inefficient air filtration, and poor ventilation. The major approaches to the study of IAQ have involved investigating the role of ventilating systems and pollution concentrations in response to worker complaints (Zyla-Wisensale and Stolwijk 1990). Many studies on the relationship between IAQ and worker productivity suffer from the Hawthorne effect (Roethlisberger and Dickson 1939), in which the subject's awareness of being studied influences the outcome.

A survey administered by BOMA (1988) points out that the issue of IAQ, as perceived by the occupants, is the fifth most frequently cited problem in buildings. The respondents of the survey also claimed that 21% of their organization's productivity would improve if IAQ problems were eliminated.

The "Indoor Environmental Quality" Concept

Just when employers, employees, and government officials were becoming comfortable with the concept of IAQ, a new and more comprehensive concept is coming into vogue: Indoor Environmental Quality (IEQ). According to the National Institute for Occupational Safety and Health (NIOSH), IAQ-associated complaints of eye, nose, and throat irritation, headaches, dizziness, fatigue and nausea cannot always be explained by indoor air factors alone (Bierbaum 1992). The effects of IAQ can vary widely among people, which makes the issue difficult to resolve. This is one of the reasons justifying provision of individual control over the environmental conditions at each workstation. In addition, experts believe that ergonomics and work area lighting can affect the workers perceptions of the quality of the breathing air and worker comfort. Therefore, the overall indoor environmental quality should be considered in analyzing office buildings.

There are also theories that psychological factors – stress, job satisfaction, and labor-management relations – may impact who will complain about problems associated with indoor air quality. According to Bierbaum (1992), NIOSH, which is pushing the IEQ concept, has found that IAQ-related complaints can be the result of multiple factors, such as indoor air (Chemical and microbiological contaminants, inadequate ventilation, tobacco smoke), ergonomics, workplace stress, workstation lighting and probably others. Bierbaum (1992) is further quoted as saying that "We are getting away from using the Indoor Air Quality because what we have found is you can solve the indoor air problem and not eliminate the symptoms. A lot of consequences of psychological stress are the same as what we might expect from poor air quality……but we can't look at indoor air without considering other issues."

According to Miller (1992), total IEQ is a better, more inclusive term for dealing with the concerns of white-collar workers. "When you look at the irritant-level health effects people are alleging in most cases, I think it is questionable that they could be occurring only because of the indoor air. But if you add some stress and ergonomic concerns, perhaps that's when the problems start to show up."

Indoor Environmental Factors

Many studies indicate that indoor environmental factors such as ventilation, air temperature and humidity can have profound effects on occupant performance. These are discussed in detail below. The effect of the luminous environment on worker productivity was covered elsewhere (Abdou 1997).

Effect of Ventilation

In a study on the effects of ventilation on building occupant performance, Vernon et al. (1926) obtained some evidence to point to ventilation as the factor that was probably responsible for some difference in sickness rates. In two rooms in the same factory girls were employed on the same kind of light work. Over a period of two years the average time lost on account of sickness in room A was 2.44% of the possible working time, and in room B it was 3.73%. The temperatures in the two rooms were very similar, but the air movement in room B was distinctly less than in room A. In the winter months the average air velocities
were 0.17 m/s in room A and 0.08 m/s in room B. The corresponding figures for the summer months were 0.20 and 0.14 m/s. The rooms were ventilated by plenum installations and by the opening of windows. The study showed that doubling the ventilation rate cut the time lost due to sickness in half.

During a study of the ventilation of schools, Vernon et al. (1930) obtained records of the absenteeism of about 5,000 children in 20 schools over a period of three years. Although no specific ventilation rates were measured in the schoolrooms, an attempt was made to grade the rooms according to the facilities for cross ventilation. Rooms with windows on one side only were grade 1.0. Those with windows on opposite sides were graded 2.0, and in the case of windows on adjacent sides the grading was between 1.0 and 2.0. Rooms that had windows on three sides were marked 2.8. Also, semi-open air schools where the whole side of a classroom could be thrown open were included in this study. Results show that there is a clear relationship between absenteeism and the average ventilation grading. Results are depicted in Table 2.

<table>
<thead>
<tr>
<th>Avg. Ventilation Grading</th>
<th>No. of Schools</th>
<th>No. of Children</th>
<th>% Absenteeism</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.2</td>
<td>6</td>
<td>1,560</td>
<td>7.7</td>
</tr>
<tr>
<td>1.5</td>
<td>8</td>
<td>1,934</td>
<td>9.2</td>
</tr>
<tr>
<td>1.2</td>
<td>6</td>
<td>1,466</td>
<td>10.7</td>
</tr>
<tr>
<td>Semi-open-air</td>
<td>6</td>
<td>1,352</td>
<td>8.9</td>
</tr>
</tbody>
</table>

An experimental study examined the environmental characteristics of an office building in the northeastern United States and their impact on the productivity of 228 employees (Zyla-Wisensale and Stolwijk 1990). A direct measure of productivity was the daily contribution by each worker to increasing the data system file size. The building was constructed in 1987 and incorporates computerized technology for controlling the HVAC system. The variable air volume (VAV) HVAC system consists of four packaged rooftop units, which divide the building into four stacked zones. Air is supplied to the conditioned space through ceiling diffusers or slots.

There was a substantial variation in productivity around a mean value, whether for employees as a group over the six-month test period (Fig. 1a) or for any given day (Fig. 1b), or for an individual over the test period (Fig. 1c). There existed a seasonal drift in overall productivity resulting in a mean productivity that was lower by 16% in the winter than in the summer (Fig. 1d). Weather did not seem to have an effect on worker productivity on a daily basis. An exception was a day with a five-inch snowfall. Employees farther away from a supply or return vent were more productive as were workers closer to a fluorescent light. This appeared to be the only external factor affecting productivity. The authors concluded that the day-to-day variation in productivity of the individual worker was due to factors internal to the employee rather than to external forces related to the building or to the environment.

Woods et al. (1987) reported on the effect of air-distribution systems on perceived indoor environment by occupants in an office environment. Approximately 15% were dissatisfied with "constant air volume" (CAV) system, 29% complained about VAV systems and 40% complained about HAV systems that have an "on-off" cycle. The perceived impact on worker productivity had a similar pattern: 13% of the workers believed that CAV systems had an adverse effect on their work; 24% felt that VAV systems hampered their work; and 30% believed to be adversely affected by on-off systems.

In the face of mounting evidence to the contrary, SMCA (1993) quotes a study reported in a New England Journal of Medicine indicating that a substantial increase in a building's fresh air intake has little apparent effect on the health of workers. The research was based on a 6-week test involving 1,546 workers in 4 buildings and was conducted by a team of academic researchers in Montreal, Canada. The study reports that researchers increased the supply of fresh air to the buildings by as much as 64 cfm/person, over three times the rate recommended by ASHRAE (1989). However, the number of complaints of headaches and other symptoms of SBS did not decline. Researchers could not explain their results but speculated that the age of the buildings, which range from 3 to 20 years old, may have had some effect.
On examining sick leave records of sample populations of workers in seven office buildings for evidence of correlations between average rates of absence of less than one day (regarded as possible indicators of SBS) and rates of supply of outdoor air for ventilation in Sydney, Australia, Rowe and Wilke (1992) concluded that there is no such correlation for the samples studied involving 500 workers. It was suggested that the incidence of minor illness depends on complex factors which may be related to the workplace and may include IAQ or to external circumstances or both.

It is generally estimated that there are about one million sick buildings with poor indoor air quality in the US alone, and 53% of sick building problems are the result of inadequate or improperly operated or maintained ventilation systems (SMCA 1993).

**Effect of Temperature**

Human tolerance for extreme temperatures under clothed conditions as a function of time is illustrated in Figure 2 (Bennett 1977). The right-hand curve shows that humans can stay alive at temperatures as high as 90°F (32°C) indefinitely and at temperatures above 110°F (43°C) for brief periods. The left-hand curve shows that people can stand temperatures as low as 50°F indefinitely and as low as 25°F for brief periods. Healthy, appropriately dressed people can tolerate these extreme temperatures, but McPherson (1973) reported that deaths in hospitals increase when room temperatures went outside the 60°-80°F (16°-27°C) range.

The center vertical line suggests that optimum comfort, regardless of duration, occurs at 78°F (25°C). The regions on the far right and the far left are too hot or too cold for the given duration to be safe. The inner regions are too warm or too cool for comfort. Actually, all three of these lines are misleading because they should be replaced by broad bands depending on humidity, activity and acclimatization.
To compound problems of temperature and ventilation, occupants often have little or no understanding of how the building systems work – how to make their spaces warmer or cooler, control air flow, obtain enough light, or achieve acoustic privacy. "This results in actions such as bringing in fans and heaters, blocking heat registers, tapping over air diffusers, and tampering with thermostats, actions that often increase energy expenditure, unbalance systems and reduce intended performance" (Drake et al. 1986). Therefore, some researchers question whether homogeneous or centrally controlled environments can ever be satisfactory to all users, given the diversity of people and activities that must be accommodated in contemporary office settings (Schiller 1988; Indoor Air '90).

Evidence from studies of large numbers of people working in Dutch office buildings shows that sick absenteeism due to SBS is reduced by 34% when individual workers can control their own thermal environment (Preller et al., 1990). Similar studies in UK offices also indicate that self-estimation of efficiency are significantly higher in such cases (Raw et al. 1990).

**Effect of Humidity**

In a two-year program of experimentation Green (1973) demonstrated that absenteeism in schools correlates closely with relative humidity between 15 % and 35%. However, no correlation was found between absenteeism and air temperature over a range of 20°C to 23°C. A comparison of two schools (one with air moistened, one without) showed that the 'moistened' school had 4.64% absenteeism and the 'non-moistened' school had 5.08% absenteeism. This difference was statistically significant.

A linear correlation between indoor relative humidity and absenteeism rate was obtained in 12 Canadian public schools, showing a 20% reduction in absenteeism when the average relative humidity during school hours was increased from 22% to 35%. Tests on Kindergarten children in Basel, Switzerland indicated that an increase in relative humidity from 40% to 49% with the temperature maintained at 22°C decreased the average absenteeism from 5.7% to 3% (Dimmick and Akers 1969). At a Missouri U.S. Army post the incidence of upper respiratory infections decreased from 1.33 to 1.14 (i.e., 17%) per trainee by increasing the relative humidity from 20 ± 8% to 40 ± 5% (Gelperin 1973).

The effect of relative humidity on absenteeism presumably occurs because relative humidity affects the survival of several air-borne microorganisms (Dimmick and Akers 1969). Since the absenteeism due to health problems directly affects productivity, these studies indicate the importance of controlling the indoor relative humidity in buildings. A range of 40 %–60 % RH is generally considered acceptable by ASHRAE.

The distress associated with dry air is caused by the inability of dry mucus membranes in the nose, throat and eyes to deal with airborne dust, at least for some individuals, and the drying associated with low winter humidity is increased by room temperatures at the high end of the conventional comfort zone (Abdou and Lorsch 1994).

Berglund et al (1990) proposed a thermoregulatory model to predict the effects on occupant performance when indoor conditions deviate from desirable values. Assuming the performance-discomfort relationship...
is valid for warm and cool discomfort, the authors used a two-node model to estimate the performance of difficult mental tasks in a number of situations. For example, in office conditions such a model predicts that performance is unaffected by temperatures over 4°C interval (Fig. 3). Lankilde (1973 and 1979) found mental performance unaffected over a 8°C interval, but Vernon (1948) found the frequency of accidents in a munitions factory was a minimum over a 2.5°C interval.

Figure 3. Predicted thermal discomfort and performance decrement over a range of indoor temperatures.

The predicted discomfort levels exhibited a similar variation with temperature (Fig. 6). The effect of air speed and humidity on performance can also be predicted by the model. Increasing the air speed from 0.33 0.1 m/s to 0.3 m/s and 0.5 m/s shifts the zero performance decrement level to warmer temperatures by 2°C and 3°C, respectively (Fig. 4a). Increasing the humidity shifts the zero decrement interval to lower temperatures (Fig. 4b) and may be helpful in winter when humidity levels are normally low. However, in summer with high dew point conditions, economizer cycle cooling with outside air may raise the indoor humidity level and degrade comfort and performance of mental tasks. While field and laboratory data on discomfort exist to verify the model, the effects on performance are not directly quantifiable by test results.

Figure 4. Predicted Effect on Performance Decrement

(a). Effect of Air Speed
(b). Effect of Humidity

Occupant Comfort - Performance Relationship

One of the first studies to relate job performance and job satisfaction to the quality of the physical environment in the US was carried out in the late 1970s for a furniture manufacturing company. This research linked worker comfort and performance by questioning office occupants on their degree of comfort with various environmental conditions (e.g., temperature, lighting, and seating). The study concluded that people would do more work in an average workday if they were more physically comfortable. Those workers who more often associate improvements in comfort with productivity are employees who work in a bullpen (pool) type of office (63%), regular workers (58%), persons employed in the business and professional services industries (60%), and persons employed in the banking and investment industry (61%) (Harris and Associates 1980).
The findings of a five-year analysis of questionnaires from more than 4,000 office workers and of field measurements of environmental conditions demonstrate that office environmental design affects both job satisfaction and job performance. The analysis identified the monetary value of productivity gains from selectively improved workspace conditions for managers and for professional/technical workers at about 5% of annual salary (BOSTI 1982). Preliminary findings from these and other similar studies indicate that the physical environment for office work may account for variation of 5% to 15% in employee productivity. Details are given in Lorsch and Abdou (1994a).

In a survey involving 600 U.S. office workers conducted to study their perception of their work environment, Woods et al. (1987) reported that satisfaction and productivity varied with the type of HVAC equipment. If the source of heat was local, 30% of the respondents were dissatisfied and 28% felt their work was adversely affected. With central heat, dissatisfaction dropped to 22% and work was perceived to be adversely affected by 19%. If a combination of central and local heat was used, their work was negatively affected. When cooling was introduced during summer, 32% of the respondents were dissatisfied but 18% thought their productivity was being affected. However, when no cooling was provided, 40% were dissatisfied, and nearly 34% felt their work was affected. Apparently, there was more dissatisfaction with individual than with central cooling, 29% versus 21%. No significant difference, however, was found in the perceived adverse affect on productivity: 17% and 17%, respectively.

A "building controls" company sponsored a comprehensive testing of a newly installed, individually controlled environmental system (for open-plan office work stations), consisting of desktop diffusers for air distribution, a radiant heat panel, and a unit that mounts under the desktop. A desktop control panel allowed personal control of environmental conditions: speed, direction, and temperature of the air at the workstation, as well as modulation of task lighting and white noise. A separate survey (Drake 1900) revealed that the user-controlled environmental system was an important factor in maintaining or improving job satisfaction, job performance, and group activity, while reducing distractions from work. Many users reported that they wasted less time taking informal breaks and were able to work more effectively and were better able to concentrate intensively on complex tasks (Drake et al. 1991). The gain in group productivity from user-controlled environmental system amounted to 9% (Drake 1990). Drake et al. (1991), however, added that "It is not enough to provide controls. User controls must be effective at increasing ventilation and thermal variations within the individual workstations, and the response time must be relatively short."

Stolwijk (1991) argues that psychosocial factors, such as labor-management relations and satisfaction or dissatisfaction with other factors in the work environment, can have a profound influence on the level of response of the occupants to their environment. This opinion is also shared by Brill et al. (1984), who, on reporting on a number of studies, concluded that physical variables may have little effect but that the unmeasured quality of worker-management relations may be responsible for worker output.

**Effects of Ambient Conditions**

It is well established that hot ambient conditions create a tendency toward inattentiveness. In turn, this affects the accuracy of performance, particularly when perceptual and psychomotor activities are involved (Lee 1963). Heat can bring about lassitude, which, in turn, is likely to increase the rate of accidents at work (Kamon 1978). This is clearly depicted in Figures 5 and 6 (Bedford 1949), which show the relationship between increased seasonal rise in ambient temperatures and frequency of work-related accidents.

This is further supported by Landsberg (1978) who stated that, if environment is too hot, productivity goes down and that if people do not feel comfortable they are more liable to make errors, have accidents, or perform a comparatively small amount of work. Bedford (1949) remarked that there was a close relationship between the external temperature and the output of workers (Fig. 7). Further, he noted that it is fairly certain that one's inclination for mental effort tends to diminish in hot environments and that deteriorating performance is partially attributable to insomnia due to heat. This is strongly supported by Schleissheimer (1966), who, upon performing statistical investigations, concluded that the average
performance of workers and employees drops by 10% at an internal room temperature of 29°C, by 22% at 32°C, and by 38% at 35°C.

On the other hand, the effects of the thermal environment on mental performance are not as clear as are the effects on physical performance. The levels of physiological strain or psychological stress that would be generally acceptable are not available (Jokl 1982).

Increased temperatures tend to produce errors in the performance of sustained mental tasks under the following conditions: (1) the task continues for 60 minutes or longer, (2) the task calls for rapid, coordinated hand movements or quick visual scanning, and (3) the task is highly demanding and externally paced (Sundstrom and Sundstrom 1986).

Mental tasks are unaffected by heat within physical limits of tolerance, except when they involve quick, coordinated movements. Motor tasks show a fairly consistent decline with elevated temperature when performance continues for 30 minutes or more. Heat has no consistent effect on vigilance. Simultaneous performance of two tasks shows a fairly consistent decline with heat, largely attributable to errors of omission in the secondary tasks. Details are given in Lorsch and Abdou (1994b).

While some studies have suggested some slight performance losses at more typical (but warm) room temperatures, fairly extreme temperatures are usually required to reduce people's performance. There may, however, be an "air-conditioning distraction" effect. That is, in affluent societies people have become accustomed to air conditioning (as well as heating) to achieve comfort. As conditions become somewhat too warm or too cool, individuals may distracted by their discomfort from their task (Bennett 1977). He further argues that well-motivated workers would not experience such losses. Jones (1970), however, concludes: "Existing data do not possess sufficient validity or reliability to allow prediction of the magnitude, direction or significance of performance decrement under thermal stress."

Wyon (1974) reanalyzed the data from a 1923 report of the New York State Commission on Ventilation. Typewriting efficiency at different temperatures was investigated. Subjects performed considerably more work at 20°C than at 24°C as shown in Figure 8.

Figure 5. Industrial accidents by month.  
Figure 6. Accident frequency in relation to temp. and to age of coal - face workers

Figure 7. Output In Tin Plate Manufacture In Relation To External Temperature.
Figure 8. Typewriting performance at 20°C (68°F) and 24°C (75°F) in two experiments in which all subjects experienced a temperature change in the middle of the day.

Young, fit, and experienced Morse code operators of the British Navy were acclimated to 95°F temperatures for six weeks. They were then tested for three hours by having to transcribe messages while exposed to different thermal environments (Mackworth 1946). The average number of mistakes per subject increased with increasing temperature. Results are given in Table 3. There seemed to exist a critical zone of temperature [between 90°F and 95°F (32°C and 35°C)] above which accuracy of performance of mental tasks declines. On the other hand, highly skilled operators did not show significant performance decrements until temperatures exceeded 100°F (37.8°C).

Table 3 Performance Of Highly Skilled Morse Code Operator At Elevated Temperatures (Mackworthme1946)

<table>
<thead>
<tr>
<th>Ambient Temperature (F)</th>
<th>Dew Point Temperature (F)</th>
<th>Average Mistakes Per Subject Per Hour</th>
</tr>
</thead>
<tbody>
<tr>
<td>85</td>
<td>71</td>
<td>12.0</td>
</tr>
<tr>
<td>90</td>
<td>76.5</td>
<td>11.5</td>
</tr>
<tr>
<td>05</td>
<td>82</td>
<td>15.3</td>
</tr>
<tr>
<td>100</td>
<td>87.5</td>
<td>17.3</td>
</tr>
<tr>
<td>105</td>
<td>93</td>
<td>94.7</td>
</tr>
</tbody>
</table>

A study of the effect of the environment on the efficiency of student performance was undertaken in 1916 for the New York State Commission on Ventilation. Conditions ranged from 68°F (20°C), 50% RH at 45 ft/min (0.23 m/s) air speed to 86°F (30°C), 80% RH with no air changes. It was concluded that, when an individual is urged to do his best, he does it as well under optimum as under stagnant, hot, and humid conditions. The same holds true if he is given work of no interest to him. When an individual was given the choice of doing mental work or read stories, rest, talk, or sleep, he did as much work per hour when the temperature was 75°F (24°C) as when it was 68°F (20°C) (Somers 1969).

In an experiment in which normally clothed young American subjects performed mental work at different temperatures (Pepler and Warner 1968), they were thermally most comfortable at 80.5°F (27°C), the temperature at which they exerted least effort and performed least work. They performed most work at 68°F (20°C), although most of them felt uncomfortably cold at this temperature. One may conclude from this that thermal conditions providing optimum comfort may not necessarily give rise to maximum efficiency. While this conclusion may be valid for relatively short periods of experimental duration, it is questionable whether this holds true for sustained periods of actual work. If people feel consistently uncomfortable in an office, they complain or they may not show up for work, actions which certainly negatively affect productivity.
Effects Of Air Conditioning

In three independent investigations, Schweisheimer (1966) reported positively on the effect of an improved microclimate on the productivity of workers. After the optimization of the microclimate in a manufacturing facility in Tennessee, operational costs in nylon stocking production decreased by 80%. It appeared that air conditioning also increased the mechanical aspects of production. An aluminum company in Canada had established air-conditioned rest and refreshment rooms for workers. The result was a large drop in absenteeism and worker turnover. Without air conditioning, workers at a utilities company in Detroit required 5000 man-hours for the production of 8988 work units. After air conditioning was installed only 3872 man-hours were required for 10,474 work units; i.e., worker productivity increased by 50%.

A consulting firm in Newark, New Jersey surveyed 30 plants in the New York vicinity that had installed air conditioning. They found that average annual productivity increased by 2% and absenteeism declined considerably. A saving of $70-$200 per annum per employee was reported – more than enough to pay for the air conditioning.

The General Services Administration reported a 9% improvement in productivity in air-conditioned offices in Washington, errors dropped by nearly 1%, and absenteeism decreased by 2.5%. Some of these improvements may be due to the fact that closing of the offices in hot weather is no longer necessary.

Conclusions

In many cases, occupants have been highly dissatisfied with their environment even though technical measurements indicated that current standards were being met. This highlights the need to reassess the measurements and standards in common use for commercial buildings. There are some indications that giving occupants greater local control over their environmental conditions improves their work performance, their work commitment and morals, and other positive implications for improving overall productivity within an organization. On the other hand, there is contrary evidence which states that conditions other than those produced by a good HVAC system are responsible for high productivity.

While there is no proof that maximum comfort leads to maximum productivity, there is ample evidence that an improved environment decreases worker complaints and absenteeism, thus indirectly enhancing productivity. There also exists anecdotal evidence that employees are less likely to ask for higher pay when they are comfortable at their workplace and that employees have refused job offers with higher pay from other employers when they discovered that the new environment would be less comfortable.

Although there exists contrary evidence regarding the relation between indoor environment and occupant productivity, there is little doubt that an improved indoor environment increases occupant health, comfort and work satisfaction and that indoor air quality is an important factor to the well-being of building occupants. It is estimated that productivity of 20% of the U.S. work force could be increased simply by improving the air quality of offices and that indoor air quality is associated with the Sick Building Syndrome. The same holds probably true for other nations.

Indoor environmental conditions (i.e., ventilation, temperature and humidity levels) are believed to have great impact on worker productivity. Most mental tasks are unaffected by heat within physical limits of tolerance, although the effects of the thermal environment on mental performance are not as clear as are the effects on physical performance. Over short periods, motivated workers can sustain their productivity even under adverse environmental conditions.

Some short-term laboratory experiments showed optimum performance at 80.5° F ±1° F. In other experiments it was found that, while workers were most comfortable at that temperature, they exerted least effort and performed least work in that environment. They performed most work at 68F, although most of them felt uncomfortably cold.
One could therefore conclude that temperatures providing optimum comfort may not necessarily give rise to maximum efficiency. This may be valid for relatively short-time experiments, but it is doubtful whether this holds true for sustained periods of actual office work.

Even in modern buildings, a significant number of office workers do not find their workspace environment comfortable. When air conditioning is introduced, productivity is raised in both industrial and office work locations.

In the opinion of some facility managers and researchers, productivity gains from selectively improved workspace conditions may be in the range of 5% to 15%, but no hard data exist to prove this.

References


Indoor Air ‘90. (1990) *Fifth international conference on indoor air quality and climate,* Toronto, Canada, August.


