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Health and comfort problems in air conditioned office buildings

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ABSTRACT

Experimental studies were undertaken to identify antecedent conditions of various health and comfort problems experienced by office workers in sealed, air conditioned buildings in New York City and Vancouver, British Columbia. The objective of these studies was to explore the complex interrelation between the architecture, HVAC and lighting design of office buildings where evidence suggests health and comfort problems exist.

Results indicate that occupant well being in sealed, air conditioned buildings appears to be dependent on building design and operation features.

INTRODUCTION

A number of extensive reviews have now documented that sealed, air conditioned buildings, especially modern office buildings, contain a wide variety of pollutants, often exceeding levels found outdoors (1,2,3,4).

Occupants of these same buildings often also suffer from a complex of symptoms including headaches, burning eyes, irritation of the respiratory system, drowsiness, fatigue and general malaise now termed Building Illness (5).

New modes of building construction, building ventilation and energy management have had profound affects on the manner in which buildings generate, entrap or eliminate pollutants. The contemporary architectural style of sealed building with very deep floor plans incorporating the latest in materials and mechanical and office technology have brought with them new indoor air quality problems in addition to increased energy requirements. The most relevant building features affecting indoor pollution levels very likely are:

1. the hermetically sealed, air tight shell,

2. the mechanical heating, ventilation and air conditioning system,

3. materials and equipment that contribute toxic fumes, (e.g. formaldehyde, ozone) or dusts, as residues from industrial shampoos and possibly also,

4. ultra violet light emitting lamps that help catalyze indoor photochemical oxidants.

The object of the two studies reported here was to explore the complex interrelationship between the architecture, the heating, ventilation and air conditioning system (HVAC) and lighting design of office buildings and health and comfort complaints reported by occupants.

Study 1 attempted to relate building characteristics, particularly of lighting and ventilation to prevalence and incidence of reported health and comfort problems by survey of occupants and architectural inventory of building characteristics. Buildings selected had no known history of health complaints.

Study 2 tested the hypothesis that varying types of lighting and amount of fresh air ventilation in a sealed, air conditioned office building would reduce health and comfort problems by reducing the antecedent conditions required for generation of photochemical smog.

STUDY 1: SURVEY OF OFFICE WORKERS TO ASSESS THE HEALTH EFFECTS OF BUILDING CHARACTERISTICS

Study 1 consisted of two components:

1) Development of a computer-readable, self-administered Work Environment Questionnaire to document perceived environmental conditions and prevalence of Building Illness among occupants of twelve study buildings.

2) Inventory of architectural, ventilation and lighting features for cross-building comparison of potential architectural stressors.

The Work Environment Survey was administered to 1106 office, clerical and professional workers, members of the Office and Professional Employees International Union (OPEIU), Local 153, occupying nine buildings in the New York City area. Buildings were chosen with no prior history of complaints.

The Work Environment Survey questionnaire requested detailed information about:

1) Environmental conditions (too little air movement, too much air movement, lighting too bright, lighting too dim, glare on work surfaces, unpleasant odors, temperature too cold, temperature too hot, air too dry, air too moist, air too smoky, air too stuffy, uncomfortable seating).

2) Lighting conditions (fluorescent ceiling light, fluorescent table light, incandescent ceiling light, incandescent table light, natural window light).

3) Health related symptoms (headache, dizziness, fatigue, sleepiness, nausea, skin rashes, ringing in ears, nose irritation, breathing difficulty, chest pain or tightness, racing heart, neck ache, sore arms, hands or wrists, backache, blurred vision, eye irritation, split or double vision, trouble focusing eyes, sore throat or cold symptoms, moodiness, frequent urination, depression, lightheadedness, confusion).

4) Control over environmental conditions (operable windows, ceiling lights, air conditioning, heating, ventilation).

5) Lifestyle factors and personal factors (smoking, coffee, tea, alcohol consumption, glasses or contact lenses used, etc.).

(There were other questions as well about equipment used, employment history, relations with other employees and supervisors, types of appliances used at home and others not reported on here).

All answers on health and environmental conditions were scored on a three point scale: 1 for "never or rarely", 2 for "sometimes", 3 for "often or always". Questions were so phrased that "never or rarely" or a 1 indicated a favourable, and "often or always" or a 3 an unfavourable response (For example, "Is there too little air movement?" or "Have you ever experienced headache while at work?" for which the choices were "Never or Rarely", "Sometimes" or "Often or Always" scored 1, 2, 3 respectively. Using this scoring scheme it was possible to construct Indices consisting of related questions and assign to them a score corresponding to the average rating of the individual items included in each index. (So that a score from 1 to 3 was assigned to each individual's overall rating of Environment and Health Indices).

For our present analysis we explore the effect of two environmental indices (the lighting and the ventilation index) on five health indices. Four of these health indices are composed of answers to questions about symptoms related to the visual, cardiorespiratory, musculoskeletal and neurophysiological system. The fifth index, Building Illness, is composed of those symptoms most frequently associated with complaints in modern office buildings. Table 1 summarizes the questions of which health and environmental indices were composed.

The association between indices of environmental conditions and of health is shown next in a group of tables. Each individual's health and environment index score of 1 was ranked as good, an index score of 1 to 2 as average and an index score of 2 to 3 as poor. Respondents were then classified by different environmental and health indices. The results were 3 X 3 frequency tables. Differences in frequency distribution by environmental conditions were evaluated for statistical significance by χ^2 test of Independence.

Rather than giving individual cell frequencies, the cross classifications shown in the next group of tables gives the proportion of individuals who rated their health conditions as good, average or poor. This mode of presentation was selected as the best way to observe the change in judgement on a health index for groups experiencing different environmental conditions.

Table 2 is a cross tabulation of the Visual Health Index by the Lighting Index. 84.7% of respondents ranking lighting as good also ranked their Visual Health as good and only 4.1% ranked it as poor. On the other hand, as many as 21.4% of respondents ranking lighting as poor also ranked their visual health as poor while only 40.2% ranked it as good. Tables 3 and 4 show the association between the Lighting Environment and Ventilation Indices and the group of symptoms typical of Building Illness. Both indices show a striking and highly significant association, especially the ventilation index. The same association also significant in each case results from similar comparisons between the other Environmental and Health Indices. (Not shown here).

Correlation coefficients are another way to assess the association between Environment and Health Indices. Table 5 summarizes the values of r between four environmental and five health indices. For the 1106 observations on which each value is based, all r's are substantial and highly significant (with $p<.0005$).

Next we compared the ability for occupants to control lighting and ventilation to the appropriate indices, that is, the Visual Health and the Building Illness Index. Table 6 correlates control of lighting by the Visual Health Index. On the vertical scale lighting could be either controlled, that is yes, or not controlled, or no, and on the horizontal the Visual Health Index is, as before, either good, average or poor. Significance is $p<0.002$ and $\chi^2=12.51582$, d.f.=4. Only 6% of respondents indicating ability to control lighting had poor visual health, whereas 10.9% of respondents with no lighting control indicated poor visual health. Table 7 relates ventilation control to Building Illness complaints. This Table is constructed like Table 6 with the vertical index being ventilation control and the horizontal the Building Illness Index. Of respondents only 8.8% with controllable ventilation indicated poor cardio-respiratory health, whereas nearly double that, or 15.5% of respondents indicating that they could not control ventilation had a high score for Building Illness symptoms.

There is a consistent pattern of association of factors relating both ventilation and lighting with frequency of reported illness symptoms. Respondents indicating poor ventilation and lighting environments were more likely to have health complaints than those with good ventilation and lighting environments. Respondents with control over environmental factors such as controlling mechanical ventilation, opening and closing windows and switching on and off lighting had fewer complaints about health symptoms than did respondents with no control over environmental factors.

Finally, examination of individual responses demonstrates that respondents discriminate between environmental conditions. This discrimination is especially notable for ventilation. Results of the cross tabulation between answers to the question "In your primary work area do you feel that there is too little air movement?" and the Building Illness index is shown in Table 8 and the association between "too much air movement" and Building Illness is shown in Table 9. Table 8 shows a highly significant relation between Building Illness symptoms and perceived insufficient air movement ($\chi^2=59.29$, d.f.=4, $p<0.001$). This is also shown by the approximately 4 times as many respondents in the insufficient than in the sufficient air movement group who rank high on Building Illness. On the other hand, the association between the question if there is "too much air movement" does not show any significant differences in distribution $\chi^2=6.97$, d.f.=4, $p<0.14$. Again this lack of relationship is made obvious by the comparison of the almost equal proportion of respondents in the group that scored low and high on this question. While movement of air by itself does not assure better fresh air ventilation, it seems to be so preceived and, in fact, may be the case in buildings that actually are better ventilated.

STUDY 2: THE IMPACT OF VARYING VENTILATION RATE AND LIGHTING TYPE ON OFFICE BUILDING SYNDROME

An experimental study testing the hypothesis that enhanced build up of photochemical oxidants indoors through ultra violet radiation emitted from sunlight simulating type of lighting impinging on pollutants is a major factor accounting for perceived environmental problems and Building Illness was undertaken in a sealed, air conditioned, mechanically ventilated office building. A very high prevalence of Building Illness, particularly the ever-present eye irritation and headaches had previously been documented for the study building along with a high incidence of perceived environmental problems (for detailed description of the study procedure and study population see reference 6). For example, the graph of absentee data which spans one year before and seven months after occupancy of the study building indicates a clearly increasing trend of absentee days per week after the move. Figure 2 presents a comparison of complaints of symptoms of Building Illness in the study building to controls in a nearby window ventilated office building. The study group reported a much higher rate of complaints of Building Illness symptoms than controls. Occupants of the sealed, air conditioned building reported 60% more eye irritation and 20% more headaches. Study and control groups were documented as similar in occupation (composed of office, clerical and professional workers), and similar in lifestyle factors (i.e. smoking, alcohol and coffee consumption).

For the experiment, one floor of the study building was divided into two areas. The occupants of these areas formed two separate experimental groups.

Group 1, consisting of 20 employees, was exposed to a change in air mixture only. For a two-week period the air that ventilated the floor area was mixed to a maximum capacity with outside air. The two-week test period was imbedded in a ten-week period in which the first six and last two weeks were monitored under normal ventilation conditions. Office personnel were not informed that a change in ventilation would occur.

Group 2, consisting of 23 employees, was exposed to changes of both air mixture and lighting. Test periods were preceded by a four-week control period and followed by a two-week control period during which normal conditions of ventilation and lighting prevailed. The initial four weeks of control period were followed by a two-week period during which lighting only was changed. The change was from sunlight simulating lamps emitting approximately 30 microwatts per 10 nanometers per lumen of UVA to standard cool white lamps emitting approximately 5 microwatts per 10 nanometers per lumen of UVA. During the next two-week period, full, unrestricted ventilation was introduced in addition to the lighting change. For the last two weeks the sunlight simulating lamps were restored and ventilation was again reduced to its former mixture. Succession of test conditions are schematically presented in Figure 3.

A questionnaire of perceived conditions and symptoms was given two times a week to all members of the study office for a control, a test and a final control period. Control periods preceding and following the tests were used to establish a baseline rating for environmental conditions and symptoms when normal ventilation and lighting practices were in force.

The questionnaire asked if particular environmental or symptomatic conditions existed. Answers were evaluated as either indicating improvement, worsening or no change in conditions.

Table 10 gives the percent change, all in the direction of improvement of perceived environmental conditions during the Group 1 test period. (Only those percent changes are given for which there was at least 5% change in average rating.)

Dramatic changes were perceived in air movement, heat and stuffiness. These perceptions are not unrelated to each other. A decrease in stuffiness is very likely a summary of the feeling that there is more air movement and less heat. However, it should be kept in mind that in a constant volume ventilation system of this type, it is not physically possible for air movement to actually change. The only controlled change was in the content and mixture of air which now contained more outside air. The slight improvement in perception of odor was to be expected. However, that increase was not statistically significant.

Table 11 summarizes the changes in rating of lighting quality. Lighting was felt not to be too bright but at the same time adequate. (That is, not too dark). Perception of glare improved. It is interesting, however, that there was a significant change in the perception of light quality when both air and light changes occurred over that which was perceived when lights only were changed. Differences were tested by analysis of variance and were found to be statistically significant (with $p<0.05$).

Table 12 summarizes changes in reported symptomology. Again, changes of less than 5% are not shown.

Either changing lighting or changing ventilation seems to have had some effect, but changing both lighting and ventilation simultaneously resulted in a 31.2% reduction in reported eye irritation. The consistent improvement indicates that effects were not chance events.

DISCUSSION

Humidity and temperature have been the traditional means by which the comfort levels of indoor spaces have been adjusted. To do so may have been justified but possibly only as long as ventilation was adequate. All our results show a higher association of health indices with lighting and ventilation than temperature and humidity.

The question which now appears relevant for sealed air conditioned office buildings concerns the relative importance to health related symptoms of lighting, ventilation, temperature and humidity either by themselves or in combination.

One way to explore this question is to determine the relative importance of the environmental condition index variablesto predict the health indices by use of multiple regression techniques. Briefly, the square of the single or multiple correlation coefficient gives the proportion by which the variance of a dependent variable is decreased by use of a predictor or group of predictors based on possibly related independent or co-variables.

$$r^2_{H|X_1} = \frac{\sigma^2_H - \sigma^2_{H|X_1}}{\sigma^2_H}$$

where:

$r^2_{H|X_1}$ is the square of the Pearson Product Momenet Correlation Coefficient between the dependent Health Index Variable, H, and the independent Environmental Index, X_1.

σ^2_H is the Variance of the observed Health Index Scores.

$\sigma^2_{H|X_1}$ is the Variance of the best estimate of Health Index Score, H, as a function of X_1.

and similarly,

$$r^2_{H|X_1,X_2,X_3\ldots X_n} = \frac{\sigma^2_H - \sigma^2_{H|X_1,X_2,X_3 \ldots X_n}}{\sigma^2_H}$$

where:

$r^2_{H|X_1,X_2\ldots X_n}$ now is the correlation between the dependent Health Index Variable, H, and a number of environmental indices X_1, X_2 ... X_n.

$\sigma^2_{H|X_1,X_2\ldots X_n}$ now is the Variance of the best estimate of the Health Index Score, H, as a function of X_1, X_2 ... X_n.

The relative importance of an environmental index X_j can be assessed by the increase in multiple r^2 following the inclusion of X_j as one of the predictor variables. (For further discussion, see Reference 7.) Table 13 shows the proportion in variance of different health indices accounted for by their correlations with the four environmental indices of ventilation, lighting, temperature and humidity. For instance, the variance of Building Illness scores is reduced by 7.8% using the ventilation index score as a predictor. The reduction in error variance is increased to 10.4 percent adding the lighting index but is not further reduced by adding temperature and humidity indices. Similar relationships are true for the other health indices. In each case the change in proportion of saved variance is statistically significant when lighting is added to ventilation ($p<.01$) but not when temperature and humidity are added. While this analysis is far from definitive, it strongly supports our observations that the major causes of Building Illness and other health and comfort complaints among inhabitants in modern office buildings is caused by ventilation and lighting factors.

Our hypothesis of the dominant importance of ventilation and lighting for occupant health and comfort is further supported by the striking results of study two. These results suggest a potential interaction between the ultra violet emitting fluorescent lamps (standard for modern office buildings) and contaminants present in the indoor air with the possible generation of photochemical smog. With the reduction of the antecedent conditions, that is removal of the ultra violet lamps and increased fresh air supply, eye irritation, an ever-present symptom of Building Illness, was reduced dramatically.

Humidity and temperature control, no matter how effective, will not compensate for an inadequate supply of fresh air. Artificial lighting designed to compensate for reduced glazing area may enhance photochemical reactions.

To avoid potential health and comfort risks building designers should consider other methods besides reducing fresh air ventilation and reduced glazing area to achieve energy savings in modern, sealed, air conditioned office buildings.

ACKNOWLEDGEMENTS

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Table 1. Groups of Symptoms Used to Construct Health and Environmental Indexes

Health Indexes	Environment Indexes
Visual .blurred vision .eye irritation .split or double vision .trouble focusing eyes	Lighting .lighting too bright .lighting too dim .glare on work surface
Cardiorespiratory .nose irritation .breathing difficulty .chest pain or tightness .racing heart	Ventilation .too little air movement .too much air movement .air too stuffy
Musculoskeletal .neck ache .sore arms, hands or wrists .backache	
Nuerophysiological .headache .dizziness .fatigue .sleepiness .moodiness .depression .lightheadedness .confusion	
Building Illness .headache .fatigue .nose irritation .eye irritation .sore throat or cold symptoms	

Table 2. Proportion of individuals who rated their lighting environment as Good, Average, and Poor, also rating the effect on their Visual Health as Good, Average and Poor.

VISUAL HEALTH	LIGHTING ENVIRONMENT INDEX: Good	Average	Poor	Number of Cases
Good	84.7	66.1	40.2	777
Average	11.2	22.1	38.5	219
Poor	4.1	11.8	21.4	110
	100.0	100.0	100.0	
Number of Cases	411	578	117	

χ^2=97.44 d.f. = 4 p<.001

Table 3. Proportion of individuals who rated their lighting environment as Good, Average and Poor, also rating their Building Illness Symptoms as Good, Average and Poor.

BUILDING ILLNESS	LIGHTING ENVIRONMENT INDEX: Good	Average	Poor	Number of Cases
Good	55.0	38.9	21.4	476
Average	37.5	45.7	46.2	472
Poor	7.5	15.4	32.5	158
	100.0	100.0	100.0	
Number of Cases	411	578	117	

χ^2 = 73.52 d.f. = 4 p<.001

Table 4. Proportion of individuals who rated their ventilation environment as Good, Average, and Poor, also rating their Building Illness symptoms as Good, Average, and Poor.

BUILDING ILLNESS	VENTILATION ENVIRONMENT INDEX: Good	Average	Poor	Number of Cases
Good	64.7	45.6	25.0	476
Average	32.4	42.8	47.8	472
Poor	2.9	11.6	27.2	158
	100.0%	100.0%	100.0%	
Number of Cases	139	699	268	

χ^2 = 89.36 d.f. = 4 p<.001

TABLE 5: **Correlations Between Scores for Environmental Conditions and Health Indices.***

HEALTH INDEX	ENVIRONMENTAL INDEX			
	Ventilation	Lighting	Temperature	Humidity
Visual	.199	.282	.161	.184
Cardiorespiratory	.254	.231	.175	.191
Neurophysiological	.256	.230	.133	.179
Musculoskeletal	.246	.209	.153	.183
Building Illness	.280	.250	.159	.193

* Each of the correlation coefficients in this table are based on 1106 questionnaires. The percentile values of r for 1000 Degrees of Freedom when $\rho = 0$ are .01 for r = .073, .005 for r = .081 and .0005 for r = .104

Table 6. Proportion of individuals rating their control of lighting as yes or no also rating their Visual Health as good, average and poor.

CONTROL LIGHTING

VISUAL HEALTH	Yes	No	Number of Cases
Good	82.0	67.7	745
Average	12.0	21.4	215
Poor	6.0	10.9	109
	100.0	100.0	
Number of Cases	150	919	

$\chi^2 = 5.29$ d.f. = 2 p<.002

Table 7. Proportion of individuals rating their control of ventilation as Yes or No also rating their Building Illness symptoms as Good, Average and Poor.

CONTROL OF VENTILATION

BUILDING ILLNESS	Yes	No	Number of Cases
Good	50.4	41.0	439
Average	40.7	43.5	451
Poor	8.8	15.5	154
	100.0	100.0	
Number of Cases	113	931	

$\chi^2 = 5.29$ d.f. = 2 p<.07

Table 8. Proportion of individuals rating Too Little Air Movement as Never, Sometimes and Often, also rating their Building Illness symptoms as Good, Average and Poor.

TOO LITTLE AIR MOVEMENT

BUILDING ILLNESS	Never	Sometimes	Often	Number of Cases
Good	59.9	45.3	31.1	476
Average	33.8	42.2	46.2	472
Poor	6.3	12.4	22.7	158
	100.0	100.0	100.0	
Number of Cases	304	419	383	

$\chi^2 = 59.29$ d.f. = 4 p<.001

Table 9. **Proportion of individuals rating Too Much Air Movement as Never, Sometimes or Often, also rating their Building Illness symptoms Good, Average and Poor.**

TOO MUCH AIR MOVEMENT

	Never	Sometimes	Often	No. of Cases
Good	43.1	42.7	43.8	476
Average	41.5	47.0	37.5	472
Poor	15.5	10.3	18.8	158
	100.0	100.0	100.0	
Number of Cases	742	300	64	

$\chi^2 = 6.97$ d.f. = 4 p<.14

Table 10: Percent changes in ratings of quality of ambient air conditions of Group 1 from Control (restricted outside air ventilation) to experimental (full outside air ventilation) phases. Positive values indicate perceived shifts to be better quality.

Question	Percent Changes
Is there too much air movement	--
Is there too little air movement?	+57.7*
Is it too cold?	--
Is it too hot?	+47.5**
Is there too much humidity?	--
Is there too little humidity?	+11.4
Is the air too stuffy?	+69.00**
Is there an unpleasant odor?	+ 7.60

* p of rating change by chance <.05
**p of differences by chance <.01
-- changes less than 5%

TABLE 11: Percent changes in ratings of quality of lighting conditions by Group 2 when lighting was changed and when air quality was changed. Positive changes indicate perceived shift to better quality.

Question	Percent Change for Light (but not air Change)	Percent Change for Light and Air Change
Is the lighting too bright?	+ 19.2	+ 26.7
Is the lighting too dark?	—	—
Is there too much glare?	+ 22.8	+ 28.3

TABLE 12: Percent decrease in symptoms during periods of full ventilation, light change, and light change plus full ventilation.

	Group I	Group II	
Symptom	Full Ventilation	Light Change	Light Change and Full Ventilation
Eye Irritation	6.8	8.0	31.2*
Headaches	--	--	19.3
Dizziness	--	--	--
Nausea	--	--	5.7
Sleepiness	17.4	9.4	10.7
Irritability	--	10.4	11.6
Change of Mood	--	9.3	11.6
Reduced Concentration	14.8	10.3	11.5
Depression	--	--	--
Elation	--	--	--

-- less than 5% change
* p of change, change $\angle$ .01

TABLE 13: Percent of Reduced Error Variance of Health Indices due to Ventilation, Lighting, Temperature, and Humidity Indices as Multiple Predictors.

	HEALTH INDICES				
Using as Predictor Variables Indices of	Building Illness	Visual Illness	Cardio/ Respiratory Illness	Neuro/ Physiological Illness	Muscular/ Skeletal Illness
Ventilation	7.8	4.0	6.4	6.6	5.9
Ventilation Lighting	10.4	9.0	8.7	8.8	7.6
Ventilation Lighting Temperature	10.5	9.3	9.0	8.8	7.8
Ventilation Lighting Temperature Humidity	10.5	9.4	9.1	8.8	7.9

FIGURE 1

ABSENTEE RATE SCATTERGRAM
PRE- AND POST-OCCUPANCY OF STUDY BUILDING

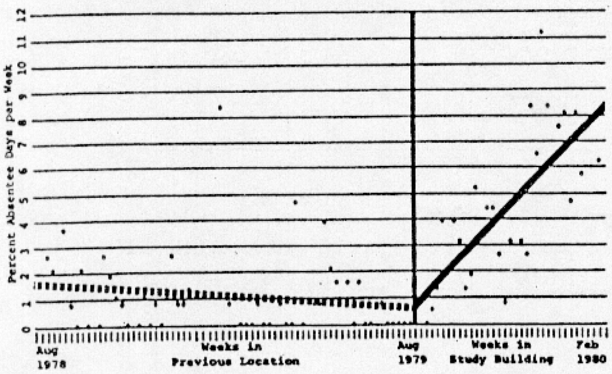

FIGURE 2
SYMPTOM DISTRIBUTION BY GROUP

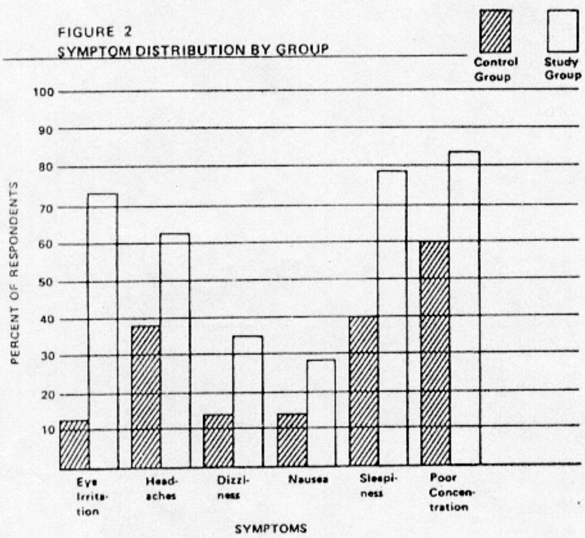

FIGURE 3
SUCCESSION OF TEST CONDITIONS

WEEK OF STUDY	1	2	3	4	5	6	7	8	9	10
GROUP I	•	•	•	•	•	•	V	V	•	•
GROUP II	•	•	•	•	L	L	X	X	•	•

• NORMAL AIR AND LIGHTING CONDITIONS
V VENTILATION ONLY CHANGES
L LIGHTING ONLY CHANGES
X BOTH VENTILATION AND LIGHTING CHANGES