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ISO-ANNOYANCE LINES FOR SELECTED LINKED PAIRS OF INDOOR CLIMATE PARAMETERS

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ABSTRACT

Most of the indoor climate research has been done in countries in the temperature region. Many of these are developed countries having resources to build good buildings and for indoor climate research. It has been a consensus in the developed societies that it is economically justified to aim at providing optimal indoor environments for students, office workers and others who work indoors. Either legislators, designers and builders in developing countries in tropical regions are often forced to use the expensive and possibly inappropriate standards from developed countries or they may adapt solutions which have no formal scientific basis. There is therefore a need for fundamental and applied research focused on the indoor climate needs of developing countries in hot and humid tropical regions.

Achieving optimized partial improvements of the indoor climate may often be better than to know all optimal levels. The purpose of this study was to investigate the relative importance of temperature, noise, draft and window area when two of these parameters are linked. Thirty (30) heat-acclimatized subjects participated in 10 exposures in single person climate chambers. Each exposure lasted three hours. During an exposure, the subject was free to optimize the operative temperature at a link to either draft, noise or window area. For each pair of parameters, three linear links were tested. A reference exposure was furthermore included without any link. Results show that a decrease in operative temperature of 1 °C gives the same decrease in annoyance as approximately 0.1 m/s decreased air velocity, 7 dB (A) decreased noise level or 0.5 m^2 increased window area. The used trade-off method may have numerous other research applications.

I. Introduction

Indoor climate studies have resulted in building codes that often give a positive input to the lives of people. Knowledge about particular problems in hot and humid tropical climates is still limited. Developing countries in hot and humid regions face particular restraints in the adoption of many technical solutions to indoor climate problems. Specifically, the installation and running costs of many solutions known from developed countries may be prohibitive. There is a need for fundamental and applied research focused on the indoor climate needs of developing countries in hot and humid tropical regions.

Predicting comfort levels has been conventionally done by single-parameter studies. The focus of this report is to determine the trade-off when temperature is linked with the parameters of window area, air velocity and noise in a warm climate.

In a warm climate when resources for air conditioning are limited, partially or entirely blocking a window in order to decrease the heat load in a space may be done but this reduces environmental contact. Ne'eman and Hopkinson (1970) have shown that sky luminance and artificial lighting levels are not the main factors which govern the choice of window size but rather visual contact with the outside which relieves the sense of enclosure. It may therefore be more acceptable to allow the temperature to increase and still have visual contact with the surroundings.

Increasing the air velocity in a space by using a fan is a well-known means of reducing heat stress. The increased air velocity may however result in draft annoyance. The sensation of draft created by air velocities has been studied by Fanger et al. (1988). The study gave maximum air velocities for comfort at neutral temperatures - when there was no sensation of feeling slightly warm or slightly cool. For the typical application where fans are used to reduce heat stress, the study may have limited relevance.

Some air-conditioners are rather noisy when turned on. The noise from an air conditioning unit will reduce people's willingness to reduce the temperature in a warm room. Clausen et al. (1993) have tried t establish equally comfortable environments by varying either noise, temperature or air quality. Their experiments were performed with only one parameter at a reduced level at a time. A more realistic situation where the parameters are linked was not attempted. Makers of air conditioners have at present limited scientific basis for deciding the relation their units should have between cooling effect and noise generation for users to consider them beneficial.

Often, decisions on the balancing of two indoor climate parameters are made by building designers. Because there have been very few scientific studies to date for this balancing of parameters, the risk is that the chosen balance points will not be in agreement with the wishes of the building users. There is an obvious need for empirical verification of the optimal or desired trade-off between parameters of the indoor climate.

II. Method

Trade-off effects were studied using heat acclimatized human subjects in climate chambers with a fast system for temperature control. There single-person climate chambers were made for this study. Thirty (30) paid human subjects participated in ten exposures each lasting approximately three hours in the chambers. They had lived all their lives in the hot and humid tropical climate of the Philippines. Santos (1998) shows data for the subjects including the average time they reported to spend in air-conditioned spaces in the paper. Each subject was in a randomized plan exposed to temperature at three different linear links to either recorded noise from an air conditioner, air velocity from a stand fan, or window area. A reference exposure where temperature was not linked with the trade-off parameters was furthermore included. The subjects were given instructions to optimize their chamber environments by giving temperature votes on the Bedford scale. They were made aware that a cooler temperature closer to thermal comfort would reduce the window opening, increase the noise level, or increase the draft in a consistent way through each exposure. They were not getting any further information but initial experimenting was encouraged. In the base exposure, they could freely vote for the temperature they felt most comfortable with without any window, draft, or noise cost.

Temperature and humidity were measured by an automated data logging system every 5 minutes in several locations according to the experimental set-up presented by Santos (1998). In the statistical analyses, only the average value of the data logged during the last 20 minutes of each hour was used. When the absolute value of the average vote was outside the range "Slightly warmer" to "Slightly cooler" the data were disregarded.

The climate chambers

Three single-person climate chambers were used (Garcia et al. 1997). Each chamber measured 2.27 x 2.27 x 2.27 m^3 inside. The walls, floor and ceiling of the chambers were made of two layers of plywood with 50 mm Styrofoam insulation between. The overall heat transfer coefficient of the chamber was 37.2 W/K including window and door. The chambers were all placed in a naturally ventilated room of approximately 95 m^2 with an air change rate of $2h^{-1}$. All chambers had a 0.94 m^2 double-glazed window. The view from these windows was a pleasant backdrop of trees seen through the metal grills and windows of the surrounding room. Supplementary lighting for chambers came from two 40-watt incandescent bulbs.

Window opening in the window chamber was adjusted using a sliding door on the outer side of the window. The positions of the sliding door were marked using 10 equal distances from the fully closed position to the fully open position. Figure 1 shows the inside of the window chamber.

Air velocity was generated in the draft chamber by a traditional stand fan diagonally behind the subject as shown in Figure 2. The average air velocity reaching a seated subject could be varied from less than 0.1 m/s to a maximum of 1.2 m/s by varying the input voltage to the fan. Figure 3 gives the vertical air velocity distribution in the centerline of the place for subjects at an average air velocity of 1 m/s.

Noise was generated in the noise chamber by playing back a pre-recorded tape of noise from a window air-conditioner. Noise level adjustments were made by adjusting the volume control knob on the playback equipment. Speakers where located on opposite corners in the noise chamber as shown in Figure 4.

III. Results

Figure 5-7 shows respectively the mean window area, air velocity and noise versus mean operative temperature for each subject during the last 20 minutes of each exposures in the chambers. Lines for the cost ties are shown as solid lines. The dotted lines are the curve for preferred mean changes during the used trade-off ties.

Using a computerized procedure for general linear models, several different types of formulas were tested to fit the observations. The best fitting models were found to be:

$$T_0 = 23.90 + 3.30\ 1/A \quad dA/dT_0 + 0.4\ t \qquad \text{for window area}$$

$$T_0 = 23.74 + 2.89vV - 16.49vV \ dV/dT_0 + 0.53\ t \qquad \text{for air velocity}$$

$$T_0 = 24.07 - 0.0000907N^2 \ dN/dT_0 + 0.36\ t \qquad \text{for noise}$$

T_o : Operative temperature in the chamber (°C)
A : Window area (m2)
V : Average air velocity (draft) reaching the person (m/s)
N : Noise pressure reaching a person in the chamber (dB_A)
t : Time (hours)

Removing the differentials by analytically solving the equations is possible for window area and noise leading to the following expressions for t = 3 h

$$0.5T_0^2 - 25.31T_0 = 3.30 \ \ln A + K \qquad \text{for window area}$$

$$0.5T_0^2 - 25.15T_0 = (0.333)\ 0.0000907N^3 + K \qquad \text{for noise}$$

A and T_0 respectively N and T_0 gives constant annoyance for constant K.

For air velocity, the differential equation may not be solved analytically. Geometrically constructed solutions for the air velocity equation are shown in Figure 6 with graphical presentations of the analytical solutions for the equations for window area and noise. The figure may be used to determine whether a change in the depicted pairs of parameters will be perceived as an overall improvement of the opposite.

IV. Discussion

These experiments reveal a significant trade-off between temperature and decreased window area, increased draft and increased air-conditioner noise. This clearly shows the power of the developed and applied experimental method compared to conventional means of predicting comfort levels from single-parameter studies.

Figure 5 -7 may be used as guides to improvements in user's perception of overall indoor quality when for example using air velocity or blockage of windows as a means to reduce heat stress. Makers of air-conditioning equipment may use the figure to evaluate the effect of noise reduction measures for their equipment.

During the window and air velocity exposures the preferred operative temperature was reduced by an average of 0.50 °C per hour of exposure while the reduction was only 0.36 °C per hour during the noise exposures. The temperature reduction is probably caused by subjects relaxing more and more therefore getting a lower metabolic rate. The higher noise levels probably cause some arousal, which counteracts this effect.

Results show that decreasing the opening of a window at a distance of 1.1 m by approximately 0.95 m^2 is perceived to be equally annoying as a 1 °C increase in operative temperature for conditions similar to these experiments. This means that a window view, 1.1 m away, must not be reduced by more than 0.95 m^2 for every 1 °C temperature reduction or people may not want to reduce the opening in order to reduce the temperature. Also, the smaller the window opening, the less people would want to decrease the window opening. Figure 5 shows iso-annoyance lines and may be used to determine whether there is an improvement in the over-all environment when both operative temperature and window area are changed.

Increasing the average air velocity from a stand fan by approximately 0.16 m/s is perceived equally annoying as a 1 °C increase in operative temperature for conditions similar to these experiments. The higher the draft level, the more people would want to increase temperature if this would reduce the draft. Figure 6 shows iso-annoyance lines and may be used to determine whether there is an improvement in the over-all environment when both operative temperature and average air velocity are changed.

Finally, increasing the air conditioner noise by an average of approximately 7.1 dB_A is perceived equally annoying as a 1°C increase in operative temperature for conditions similar to these experiments. This means that the noise that a cooling device generates must not exceed 7.1 dB_A for every 1 °C temperature reduction or people may not want to use it. Also, the higher the air conditioner noise level, the more people would want to increase temperature if this would reduce the noise. Figure 7 shows iso-annoyance lines and may be used to determine whether there is an improvement in the over-all environment when both operative temperature and noise level are changed.

Thirteen (13) window-mounted air conditioners were surveyed in offices in Quezon City, Philippines and the average noise level was 62.5 dB_A with a standard deviation of 5.2 dB_A. Several of these were more noisy than recommendable for the heat stress relief they provided.

V. Conclusions

These experiments reveal a significant trade-off between temperature and window area, draft and air-conditioner noise. This shows the power of the developed and applied experimental method. It is also shows limitations in conventional means of predicting comfort levels from single-parameter studies.

Trade-off studies have been shown to give relevant results. This type of unified scaling research may give important information on the proportions of user's perceptions of the indoor climate. Specifying the optimum trade-off between linked parameters is a next-best solution when resources are scarce. Continuing research activities in these and related areas can do much to assure the best possible quality of the indoor environment in countries with limited economies as this type of research may become the basis for updating regulating codes.

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Figure 1. Subject seated in the window chamber. The partially opened window can be seen beside the subject.

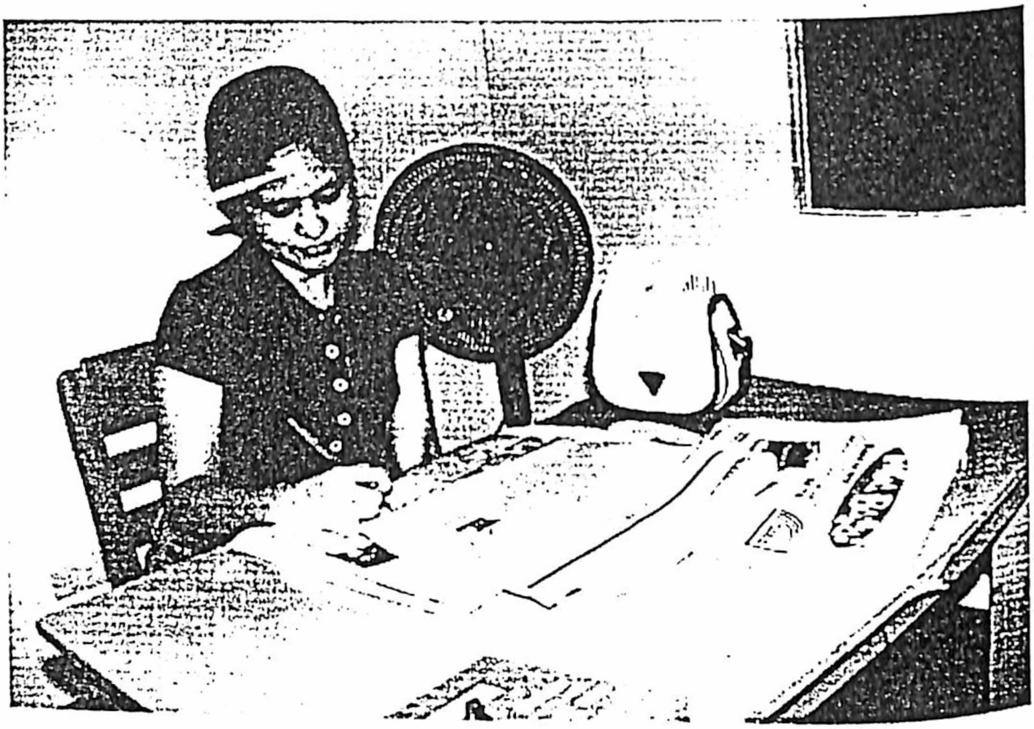

Figure 2. Subject seated in the draft chamber.

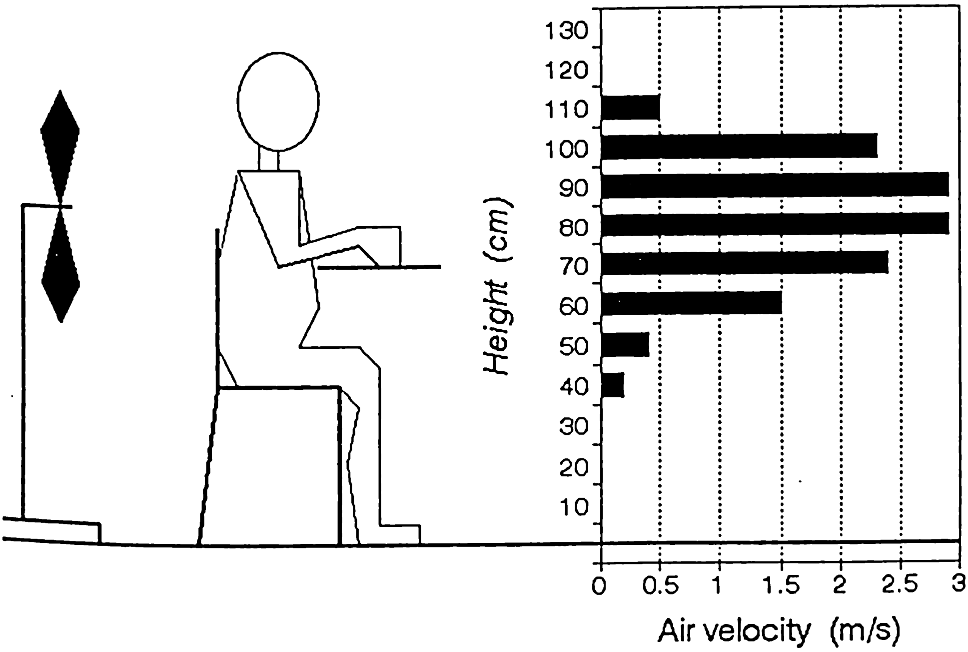

Figure 3. Air velocity distribution 90 cm from the fun at the centerline of the subjects. Drawing only for approximate reference.

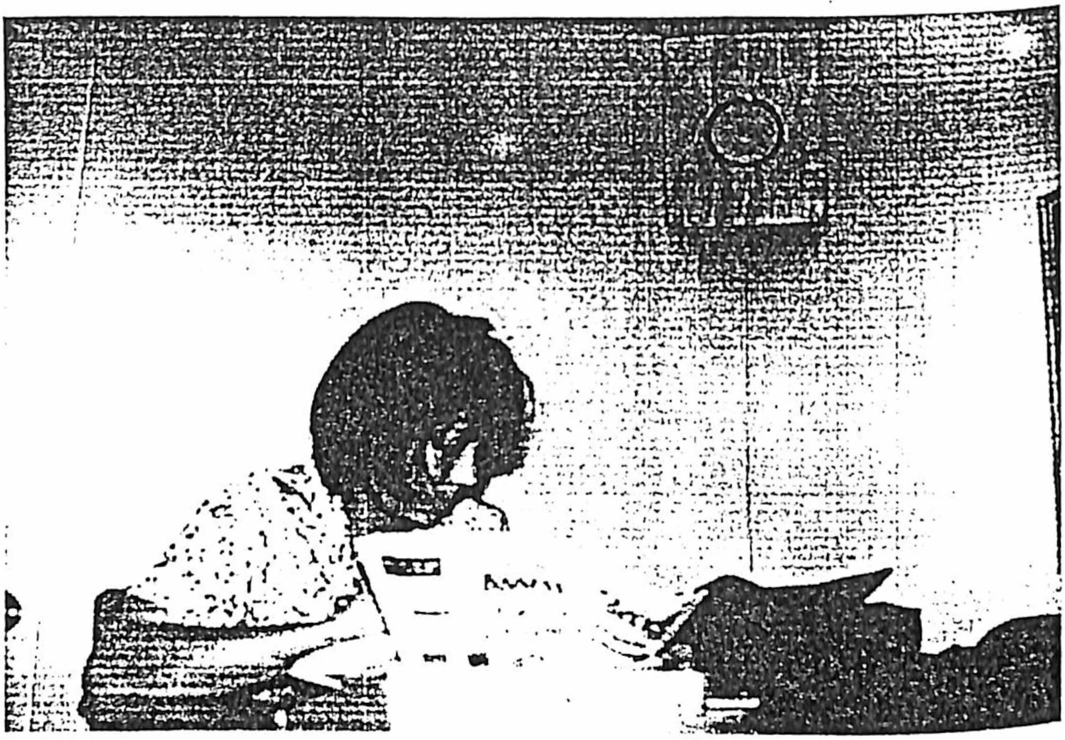

Figure 4. Subject seated in the draft chamber. One of the two speakers can be seen behind the subject.

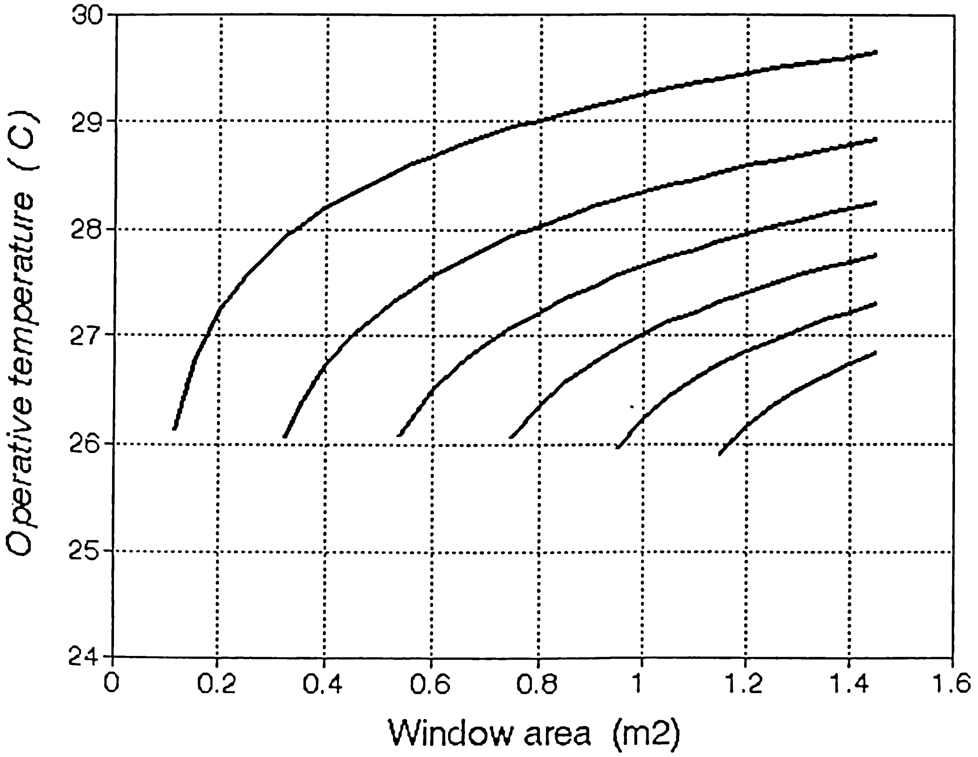

Figure 5. Lines of constant annoyance when operative temperature is linked with window area 1.1 m away.

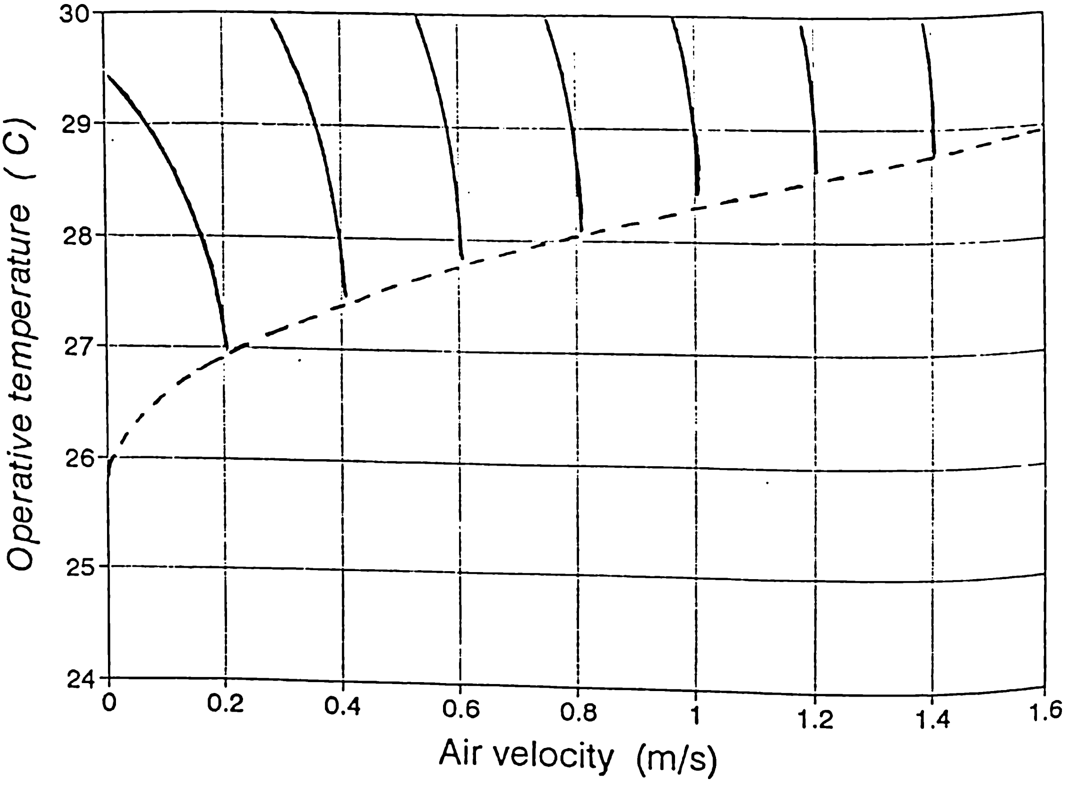

Figure 6. Lines of constant annoyance when operative temperature is linked with air velocity.

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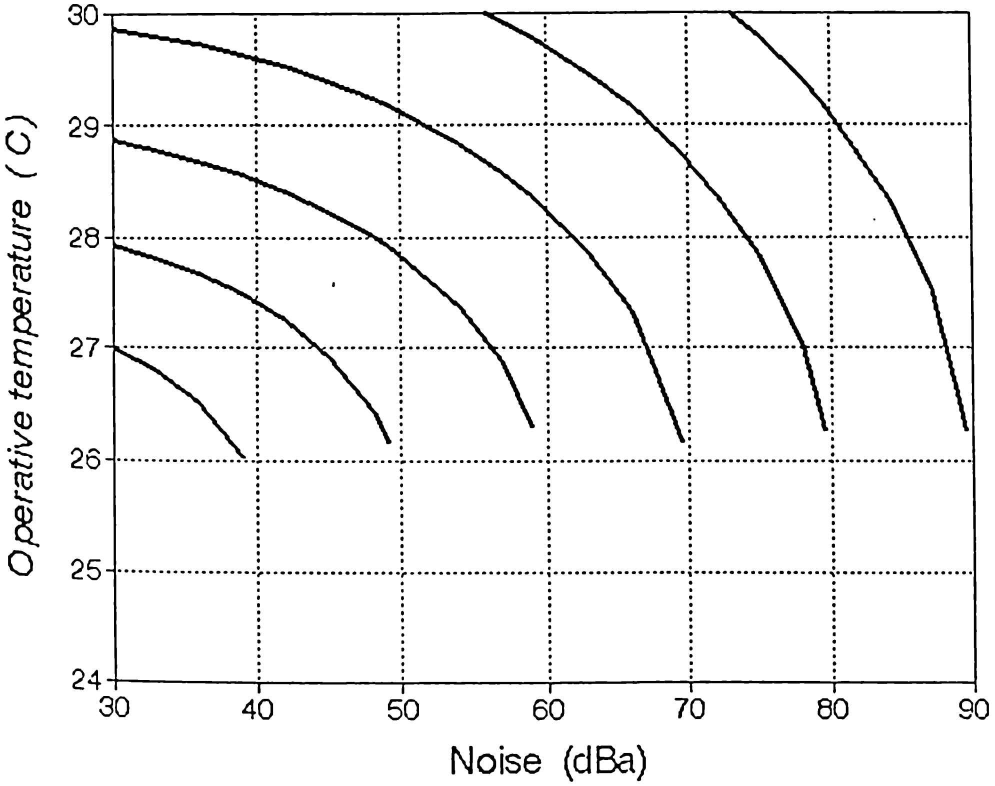

Figure 7. Lines of constant annoyance when operative temperature is linked with air conditioner noise pressure.