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Performance of noise indices in air-conditioned landscaped office buildings

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Noise measurements and a questionnaire survey were carried out in air-conditioned landscaped offices in the present study in an attempt to find out what existing noise index gives the best correlation with the auditory sensation feeling of office workers. Results from statistical analyses show that the *Equivalent Sound Pressure Level* is the best among the 14 commonly used noise indices for this purpose. It is also found that the less commonly used *Zwicker's loudness level* performs better than the commonly adopted *Noise Criterion curves* and *Noise Rating curves* in predicting auditory sensation of office workers in air-conditioned landscaped offices. The performance of the 14 noise indices in predicting auditory comfort are compared. © *1997 Acoustical Society of America.* [S0001-4966(97)05508-2]

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INTRODUCTION

One of the most controversial issues in building up a good indoor environment is the setting up of a suitable noise criterion. Noise affects human beings both physiologically and psychologically as discussed in Kryter.[1] A poor acoustical environment will lead to excessive mental stress, loss of concentration, etc., and, for commercial offices, these symptoms mean loss of productivity. The importance of noise control in buildings is reiterated by Lord and Wilson[2] in a discussion on the environmental design of buildings.

Noise inside a building comes from human activities, building services, and outdoors. The contribution of outdoor noise depends very much on the sound transmission loss of the building facade. Examples of research and surveys on this topic include Craik and Thancanamootoo[3] and Elmallawany.[4] However, most people today are working in air-conditioned office buildings whose facades have relatively higher sound transmission loss so that sound transmission from the outdoors to the indoors is insignificant when compared to those generated by the building services, such as the air-conditioning system, and human activities.[5]

A good acoustical environment implies good control of noise to keep its level and frequency content within the acceptable range for human beings. This issue deals with human feeling, which is very subjective in nature. However, some objective parameters are required for the design and assessment of an indoor acoustical environment. Many different noise indices have been developed to suit this purpose, among which the well-known equivalent sound pressure level $L_{\mathrm{Aeq},T=5\ \mathrm{min.}}$, the *noise Criterion curves (NC)* of Beranek,[6] and *noise rating curves (NR)* of Kosten and van Os[7] are commonly used nowadays. These indices are easy to interpret and measure. However, the search for better indices never ceases. Studies on the noise inside air-conditioned office buildings have been rigorous for many decades. Keighley[8] gave a discussion on the determination of acceptability criteria for office noise while Hay and Kemp[9] proposed an office noise index based on percentile noise level,[1] which is not commonly used today. There are still many other noise indices that may be able to predict human comfort effectively. This list includes the *room criteria (RC)* of Blaizer,[10] *loudness levels* of Stevens[11] and Zwicker,[12] *balanced noise criteria (NCB)* of Beranek,[13] etc. Details of this list will be given later. A particular review on the criterion for controlling indoor air-conditioning noise can be found in Kingsbury.[14] Because of the existence of so many noise indices, it is important to test how well they can represent human auditory rating for future use in the setting up of suitable noise index for building environmental noise control. It is assumed at this stage that their performance may depend on the type of environment. The present study focuses on air-conditioned landscaped offices.

In the present study, sound level and spectral measurements of noise in one-third octave bands were carried out in parallel with a questionnaire survey in 26 air-conditioned landscaped offices during their normal hours of operation. Therefore, the noise data in this study include not only the contribution from the air-conditioning system, but also those from human activities and office machines. The performance of various noise indices in correlating with the auditory rating of the office workers is discussed. It is hoped that the most effective index and a clue for future development of noise index for office buildings can be found.

I. NOISE MEASUREMENT AND SURVEY

Noise levels at different locations in the 26 air-conditioned landscaped offices were measured using a Brüel & Kjær 2236C precision sound level meter while their spectral content in one-third octave bands were obtained by Brüel & Kjær 2144 real-time frequency analyzer with Brüel & Kjær 4145 condenser microphone. The questionnaire asked the office workers to rate their feeling towards the acoustical environment on an unbiased linear seven-point scale at the time the measurements were being done. The present adopted scale is similar to that used by Tang *et al.*[5] and is shown in the Appendix. The rating obtained from the scale,

TABLE I. Abbreviations of noise indices.

Noise indices	Abbreviation	Unit
Equivalent sound pressure level	$L_{\mathrm{Aeq},T=5\ \mathrm{min.}}$	dB
Percentile level for 10% exceedence	$L_{\mathrm{A10},T=5\ \mathrm{min.}}$	dB
Percentile level for 90% exceedence	$L_{\mathrm{A90},T=5\ \mathrm{min.}}$	dB
Noise climate	$L_{\mathrm{A10},T=5\ \mathrm{min.}}-L_{\mathrm{A90},T=5\ \mathrm{min.}}$	dB
Noise criterion	NC	Nil
Preferred noise criterion	PNC	Nil
Balanced noise criterion	NCB	Nil
Noise rating	NR	Nil
Room criterion	RC	Nil
Midfrequency average level	L_{MF}	dB
Stevens' loudness	LD_s	sone
Loudness level (Stevens)	LL_s	phon
Zwicker's loudness	LD_z	sone
Loudness level (Zwicker)	LL_z	phon

which ranges from −3 to +3, represents human auditory subjective rating. A rating of −3 represents ''Very Noisy'' feeling while ratings of 0 and +3 denote, respectively, the ''Neutral'' and ''Very Quiet'' feelings. One can observe that it is much simpler than that used by Beranek[6] so as to minimize disturbance to the office workers. The ratings so obtained represent their purely primitive but subjective feelings toward their acoustical environments as a whole. It should be noted that there is no guideline for the office workers to judge their local acoustical environments so that they may base their judgment on loudness or noisiness of office noise. This rating scale is also much different from the biased scale adopted by Ko *et al.*[15] in the study of air-conditioning nuisance; that of Ko *et al.*[15] mainly deals with complaints.

Each noise measurement in the present study lasted for 5 mins. A total of 1187 questionnaire responses were obtained. Each of them was accompanied by physical noise measurements.

II. NOISE INDICES

All the noise indices presented in the foregoing discussions, except $L_{\mathrm{Aeq},T=5\ \mathrm{min.}}$ and those related to the percentile noise levels $L_{\mathrm{A10},T=5\ \mathrm{min.}}$ and $L_{\mathrm{A90},T=5\ \mathrm{min.}}$ were calculated from the one-third octave band noise spectra measured by the Brüel & Kjær 2144 real-time frequency analyzer. The noise indices involved in the present study are $L_{\mathrm{Aeq},T=5\ \mathrm{min.}}$, $L_{\mathrm{A10},T=5\ \mathrm{min.}}$, $L_{\mathrm{A90},T=5\ \mathrm{min.}}$, the noise climate $L_{\mathrm{A10},T=5\ \mathrm{min.}}-L_{\mathrm{A90},T=5\ \mathrm{min.}}$, *noise criterion*,[6] *noise rating*,[7] *balanced noise criterion*,[13] *preferred noise criterion*,[16] *midfrequency average level* (L_{MF}),[17] *loudness*, and *loudness levels* of Stevens[11] and Zwicker.[12] The first four indices are A-weighted. However, one should bear in mind that these indices may not be mutually exclusive, and this list is by no mean exhaustive. There are still some other less common indices like the *low-frequency noise rating* proposed by Broner and Leventhall[18] which is specially designed to cater for low-frequency noise environment. *Articulation index*[1] is also not presented in the present study as it is believed that this index deals with speech intelligibility and is less likely to be associated with nuisance directly. Though L_{MF} can also deal with speech intelligibility,[1] it is the arithmetic mean of the octave band levels at 500 Hz, 1 kHz, and 2 kHz which cover the most sensitive frequency range of human ear, and thus directly represents certain strength of a noise. It should also be noted from the results of Tachibana *et al.*[19] that the arithmetic average of the levels in the bands from 63 Hz to 4 kHz may give slightly better correlation with human feeling than *Zwicker's loudness level*. However, such difference in the performance of these two indices is not expected to be substantial, especially under the very subjective nature of human feeling. Thus, the index purposed by Tachibana *et al.*[19] will not be discussed in the present study.

The noise indices, except the noise level data $L_{\mathrm{Aeq},T=5\ \mathrm{min.}}$, $L_{\mathrm{A10},T=5\ \mathrm{min.}}$, $L_{\mathrm{A90},T=5\ \mathrm{min.}}$, and the noise climate which were recorded *in situ* using the sound level meter, were computed from the spectra using a self-developed computer program. The indices NC, NCB, PNC, RC, and NR were determined by the ''tangency method.'' The FORTRAN subroutine for the calculation of *Zwicker's loudness* given by Paulus and Zwicker[20] was adopted. The method for Stevens' loudness calculation simply followed that given in ISO 532.[21] For ease of reference in the foregoing discussions, the noise indices are abbreviated as shown in Table I. Suffices *s* and *z* represent Stevens and Zwicker systems of loudness estimation, respectively. The loudness level LL in phons and loudness LD in sones, no matter which loudness system is concerned, are related by the expression[21]

$$LD = 2^{(LL-40)/10}.$$

III. RESULTS AND DISCUSSIONS

Before going into the details of the discussion on the performance of noise indices, some typical octave band noise spectra obtained in the offices during normal operation hours are shown in Fig. 1. It can be observed that the noise spectra in the surveyed offices vary significantly. However, most of them show hissy nature. This is due to office activities as suggested by Fig. 2. In general, over 85% of the noise spectra obtained in the present field measurements show hissy characteristics (not shown here). Therefore, though it is well known that NCB and the composite RC rating provide a number as well as a letter showing the frequency content of a noise; the latter is ignored in the foregoing discussion.

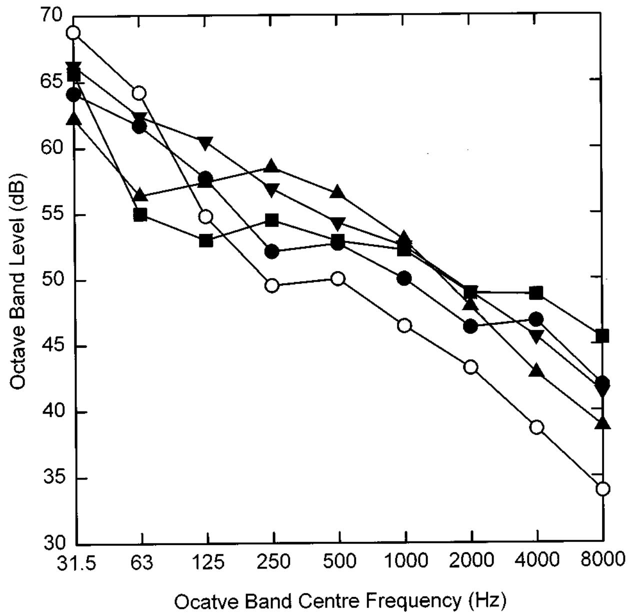

FIG. 1. Typical office noise spectra during normal operation hours. ○: Neutral spectrum; ●, ■, ▲, and ▼: hissy spectra.

The performance of noise indices is investigated through linear regression analysis. Good performance of a noise index in the present study refers to the case in which its correlation with the human auditory subjective rating is good and linear relationship with human auditory subjective rating can be established. Correlation coefficient is used for the assessment of noise index performance. Hypothesis testing procedure with the F-test at 95% confidence level illustrated in Bethea and Rhinehart[22] is also adopted to test whether the linear relationships between noise indices and the auditory sensation rating are valid. The null hypothesis H_0 is that the slope of the regression line is zero (that is, no linear relationship exists) and will be accepted if $F \leqslant F_{1,n-2,0.95}$, where n is the sample size. Only linear regression is considered in this study as it is the simplest form of analysis and visual inspection of the plots do not indicate clearly any nonlinear

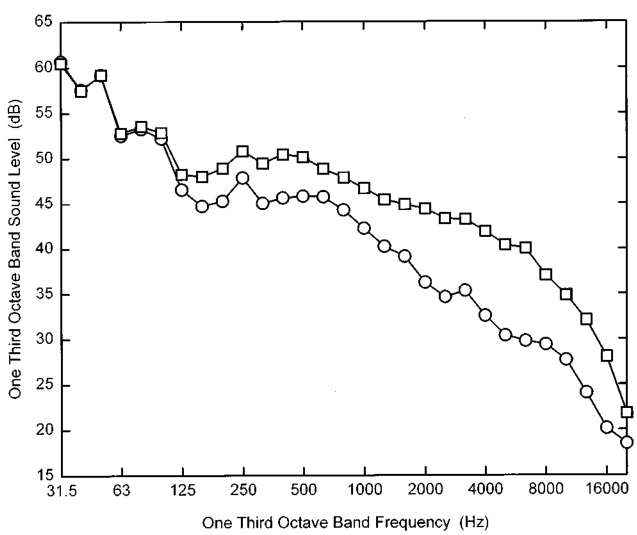

FIG. 2. Change in noise spectral content due to office activities. □: Noise spectrum during office hours; ○: noise spectrum outside office hours.

TABLE II. Interval for human auditory subjective rating averaging.

Noise index	Interval of averaging	Range
Equivalent sound pressure level	±0.5 dB	41–70 dB
Percentile level for 10% exceedence	±0.5 dB	42–75 dB
Percentile level for 90% exceedence	±0.5 dB	35–59 dB
Noise climate	±0.5 dB	2–18 dB
Noise criterion	Not applicable	NC 39–59
Preferred noise criterion	Not applicable	PNC 35–65
Balanced noise criterion	Not applicable	NCB 34–64
Noise rating	Not applicable	NR 33–70
Room criterion	Not applicable	RC 40–67
Midfrequency average level	±0.5 dB	31–74 dB
Stevens' loudness	±0.5 phon	15–130 sone
Loudness level (Stevens)	±0.5 sone	80–110 phon
Zwicker's loudness	±0.5 sone	5–30 sone
Loudness level (Zwicker)	±0.5 phon	62–89 phon

relationship. Due to the very subjective nature of human feeling, the method for rejecting outlying observations developed by Thompson[23] is adopted. Mean sensation ratings obtained from a sample of size less than five are ignored in the analysis. One index is better than another index when its R^2 and the associated ratio $F/F_{1,n-2,0.95}$ are larger than those of the latter.

Before discussing the regression results, it should be emphasized that two noises having the same $L_{\mathrm{Aeq},T=5\,\mathrm{min.}}$ will not necessarily have the same NC value because of the difference in the meanings of the two indices. This phenomenon applies to all other noise indices. Also owing to the subjective nature of human feeling, different office workers may give different ratings to the same acoustical environment. In the foregoing analysis, the human auditory sensation ratings presented are arithmetic averages within short intervals of noise indices. For example, the rating at $L_{\mathrm{Aeq},T=5\,\mathrm{min.}}=P$ dB is the arithmetic average of all votes obtained within the interval $P-0.5 \leqslant L_{\mathrm{Aeq},T=5\,\mathrm{min.}} < P+0.5$ ($a \pm 0.5$ dB interval). As there is no fractional value for NC, NCB, NR, PNC, and RC, the ratings presented with them are the straightforward means. Table II summarizes the interval of averaging and the range for each index. The noise indices discussed in the present study can basically be divided into three categories. The first category includes $L_{\mathrm{Aeq},T=5\,\mathrm{min.}}$, percentile levels, and the noise climate whose estimation does not require a knowledge of the noise spectral contents. The second one consists of *loudness*, *loudness levels*, and the *midfrequency average levels*, which are calculated from the spectral information of noise and are continuous indices. The last one refers to the group of NC, NCB, and etc. which have discrete nature and are, like those in the second category, estimated from the noise spectra. Though the emphasis of these indices is on achieving acceptable speech intelligibility and a nonannoyance shape of the noise spectrum for that speech intelligibility level,[17] it is still worthwhile to see whether they can be used to predict the very primitive but subjective feeling of office workers toward their acoustical environments.

Figure 3(a) shows the correlation between the average human auditory sensation rating S and $L_{\mathrm{Aeq},T=5\,\mathrm{min.}}$. The regression line is also shown in the figure. Though a certain

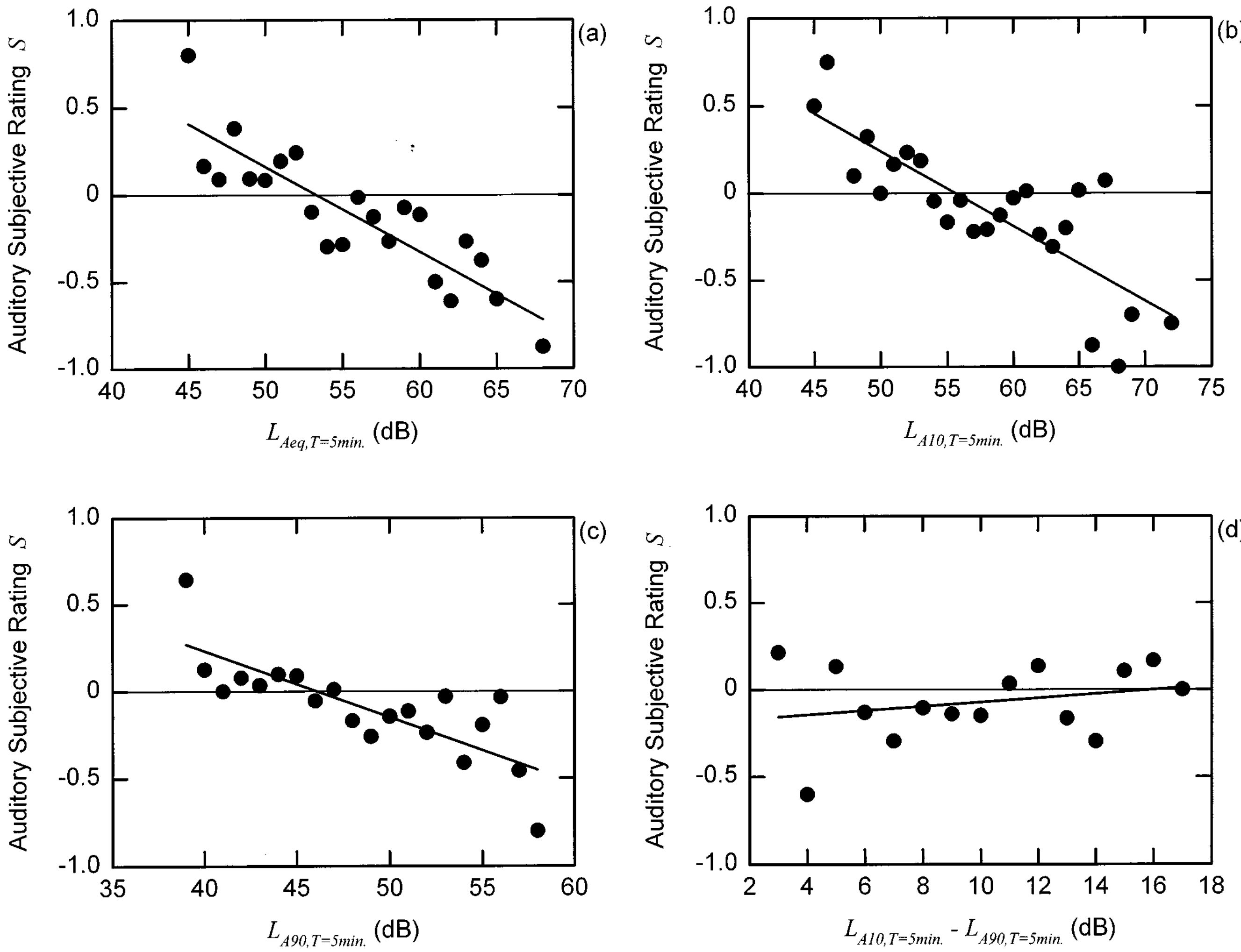

FIG. 3. Correlations between noise levels and human auditory subjective ratings. (a) $L_{\mathrm{Aeq},\ T=5\ \mathrm{min.}}$; (b) $L_{\mathrm{A10},\ T=5\ \mathrm{min.}}$; (c) $L_{\mathrm{A90},\ T=5\ \mathrm{min.}}$; and (d) $L_{\mathrm{A10},\ T=5\ \mathrm{min.}}-L_{\mathrm{A90},\ T=5\ \mathrm{min.}}$ ●: Experimental data; ———: regression line.

degree of scatter is observed, the correlation coefficient R^2 is 0.766, which is relatively high in social research. Also, $F=65.5>F_{1,20,0.95}(=4.35)$ (Ref. 22) in the hypothesis testing and thus the null hypothesis is rejected, showing that linear relationship between S and $L_{\mathrm{Aeq},T=5\ \mathrm{min.}}$ exists and the regression line should represent such relationship. The regression line predicts neutral auditory sensation at $L_{\mathrm{Aeq},T=5\ \mathrm{min.}}\approx 52$ dB, which is slightly higher than the recommendation of 50 dB in BS 8233.[24] However, this difference is minor in an environmental noise study. The present predicted neutral auditory sensation does agree with the upper limit of L_{Aeq} suggested in Reynold[25] for large offices. Similar correlation phenomena are observed for $L_{\mathrm{A10},T=5\ \mathrm{min.}}$ and $L_{\mathrm{A90},T=5\ \mathrm{min.}}$ as shown in Fig. 3(b) and (c), respectively. Though the correlation coefficients between S and these two quantities are lower than that between S and $L_{\mathrm{Aeq},T=5\ \mathrm{min.}}$ the results of the F-test are $F=44.1$ for $L_{\mathrm{A10},T=5\ \mathrm{min.}}$ and 30.1 for $L_{\mathrm{A90},T=5\ \mathrm{min.}}$ showing again that the regression lines do represent the existence of linear relationships. However, the noise climate $L_{\mathrm{A10},T=5\mathrm{min.}}-L_{\mathrm{A90},\ T=5\ \mathrm{min.}}$ does not relate to human sensation S as shown in Fig. 3(d) ($R^2=0.06$,$F=0.83<F_{1,13,0.95}=4.67$). This suggests that those noise indices which are associated with the noise climate may not be appropriate for use in air-conditioned landscaped offices. Examples of such noise indices are office noise index proposed by Hay and Kemp[9] and the noise pollution level of Robinson.[26] Results of the present statistical analysis are tabulated in Table III. In Table III, n represents the number of averaging intervals. This number varies from index to index because of the range and average interval of each index (see Table II). It should also be noted that there are missing values in the noise index distribution so that n is, in general, less than the value obtained by dividing the range by the averaging interval. Figure 4 illustrates the frequency distributions of $L_{\mathrm{Aeq},T=5\ \mathrm{min.}}$, $L_{\mathrm{A10},T=5\ \mathrm{min.}}$, $L_{\mathrm{A90},T=5\ \mathrm{min.}}$, and $L_{\mathrm{A10},T=5\ \mathrm{min.}}-L_{\mathrm{A90}T=5\ \mathrm{min.}}$. Allowing for data scatter, they appear to be quite symmetrical (skewness $s\approx 0.4$). However, that of the *noise climate* $L_{\mathrm{A10},T=5\ \mathrm{min.}}-L_{\mathrm{A90},T=5\ \mathrm{min.}}$ is relatively more skewed to the low value side.

Indices in the second category are, in general, not very well correlated with human auditory sensation as shown in Table III. Only *Zwicker's loudness level* LL_z[12] can be considered as a useful index for application in air-conditioned landscaped offices. Others are either inappropriate or very marginal. The correlation between LL_z and human subjective rating S is shown in Fig. 5(a) ($R^2=0.65$). Unlike the fre-

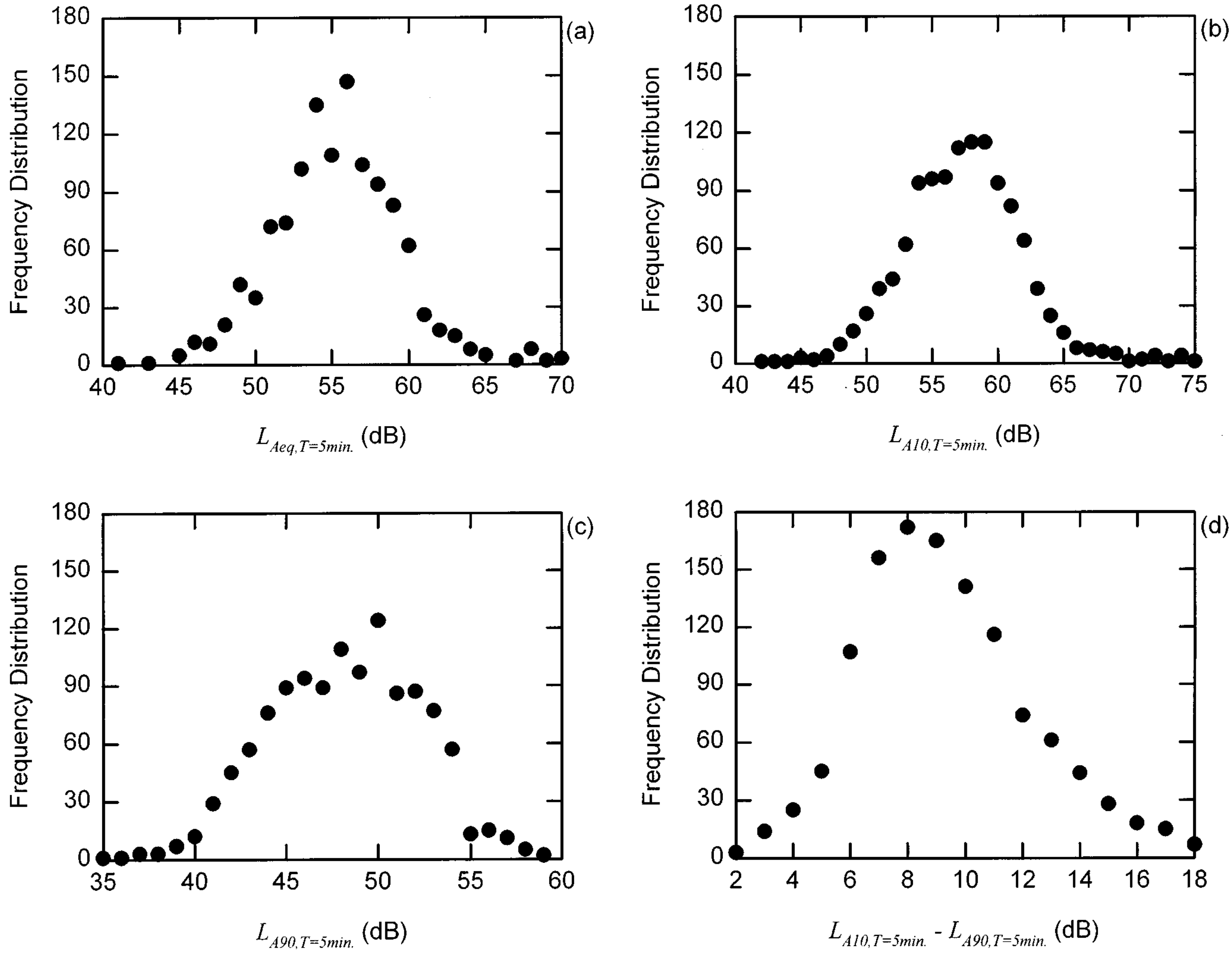

FIG. 4. Frequency distribution of noise levels. (a) $L_{\mathrm{Aeq},\ T=5\ \mathrm{min.}}$; (b) $L_{\mathrm{A10},\ T=5\ \mathrm{min.}}$; (c) $L_{\mathrm{A90},\ T=5\ \mathrm{min.}}$; (d) $L_{\mathrm{A10},\ T=5\ \mathrm{min.}} - L_{\mathrm{A90},\ T=5\ \mathrm{min.}}$.

quency distributions of $L_{\mathrm{Aeq},T=5\ \mathrm{min.}}$, $L_{\mathrm{A10},T=5\ \mathrm{min.}}$, and $L_{\mathrm{A90},T=5\ \mathrm{min.}}$, those for noise indices within this category tend to have relatively higher kurtosis (for instance, 4.17 for $\mathrm{LL_z}$, 5.41 for $\mathrm{LL_s}$, and 2.66 for $\mathrm{L_{MF}}$), showing that their occurrence is concentrated in relatively more narrow ranges [Fig. 5(b)]. As only $\mathrm{LL_z}$ appears to be related to human auditory feeling, the frequency distributions of other noise indices within this category are not presented. Figure 5(a) sug-

TABLE III. Statistical result summary.

Noise indices	Skewness (s)	Kurtosis (k)	Number of averaging intervals n	Correlation coefficient (R^2)	Value of f-test (F)	$F_{1,n-2,0.95}$	H_0
$L_{\mathrm{Aeq},T=5\ \mathrm{min.}}$	0.532	1.940	22	0.766	65.45	4.35	Rejected
$L_{\mathrm{A10},T=5\ \mathrm{min.}}$	0.457	1.700	25	0.657	44.09	4.24	Rejected
$L_{\mathrm{A90},T=5\ \mathrm{min.}}$	0.368	1.233	20	0.626	30.07	4.41	Rejected
Noise climate	0.705	0.837	15	0.060	0.836	4.67	Accepted
NC	0.096	0.630	22	0.319	10.90	4.35	Marginal
PNC	−0.132	0.340	20	0.254	6.142	4.41	Marginal
NCB	−0.252	0.775	22	0.351	10.80	4.35	Marginal
NR	0.955	4.447	23	0.362	11.93	4.32	Marginal
RC	0.927	4.941	29	0.124	3.808	4.21	Accepted
$\mathrm{L_{MF}}$	0.579	2.658	20	0.306	7.942	4.41	Marginal
$\mathrm{LD_s}$	4.187	34.33	45	0.174	9.088	4.06	Marginal
$\mathrm{LL_s}$	0.046	5.412	19	0.195	4.115	4.45	Accepted
$\mathrm{LD_z}$	4.441	36.48	17	0.386	9.409	4.54	Marginal
$\mathrm{LL_z}$	0.475	4.169	22	0.650	37.22	4.35	Rejected

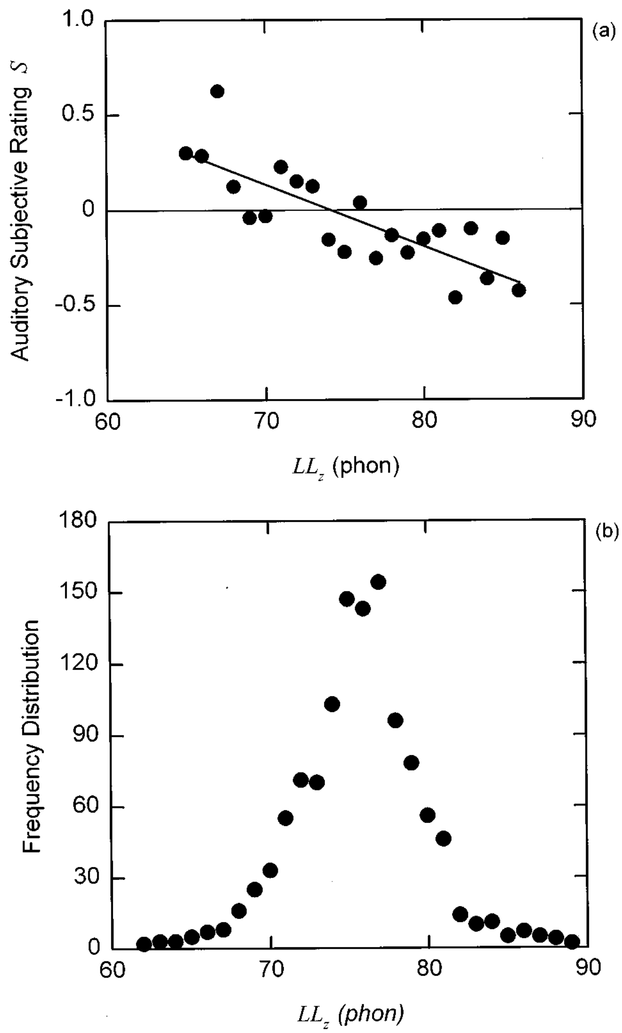

FIG. 5. (a) Correlation between *Zwicker's loudness level* and auditory subjective rating. (b) Frequency distribution of *Zwicker's loudness level*. ●: Experimental data; ———: regression line.

gests that office workers will regard the acoustical environment to be ''noisy'' when $LL_z > 74$ phons. This *Zwicker's loudness level* has not been specified, at least to the knowledge of the author, in international standards or recommendations for indoor building environmental design and noise control. The good correlation between it and human auditory subjective rating manifests its importance in dealing with human hearing comfort in air-conditioned landscaped offices.

Table III also suggests that the noise indices in the third category, which have discrete nature, do not perform very well in the prediction of human auditory sensation in air-conditioned landscaped offices. The relatively better indices are NC, NCB, and NR. For RC, the correlation is essentially not valid. Also though F for $\mathrm{PNC}=6.14>F_{1,n-2,0.95}=4.41$, the difference is too small for a reliable rejection of the null hypothesis. Figure 6 illustrates the degree of correlation between NC, NCB, NR, and human auditory subjective rating. Though these correlations are only marginally acceptable, the present results suggest that office workers, as a whole, will feel noisy when NCB>45. This agrees with the recommendation of Beranek.[27] The neutral NC value is 47 as predicted by the marginally acceptable correlation in Fig. 6 which is higher than that of 45 shown in Reynold.[25]

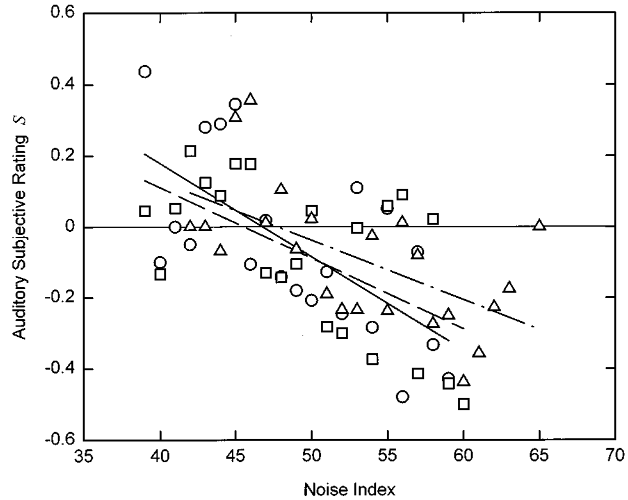

FIG. 6. Correlations between NC, NCB, and NR with auditory sensation vote. ———: Regression line for NC; – – –: regression line for NCB; –·–: regression line for NR; ○: experimental data for NC; □: experimental data for NCB; △: experimental data for NR.

Statistical results in Table III suggest that the equivalent sound pressure level $L_{\mathrm{Aeq},T=5\,\mathrm{min.}}$ gives the best estimation of the auditory subjective rating of the office workers among all the noise indices discussed in the present study at 95% confidence level. The second best index studied in the present investigation is LL_z. Results also illustrate that the performances of discrete indices NC, NCB, NR, PNC, and RC in matching subjective human auditory feeling are, in general, not satisfactory.

IV. CONCLUSIONS

In the present investigation, noise measurements and a questionnaire survey were carried out in more than 20 air-conditioned landscaped offices. The questionnaire was used for the collection of subjective ratings of the office workers towards their acoustical environment. Physical noise measurement results included the equivalent sound pressure level, the percentile levels, and the one-third octave noise spectra from which various noise indices were calculated. Performance of noise indices in correlating with the subjective human auditory subjective rating is discussed.

The noise indices considered in the present study are $L_{\mathrm{Aeq},T=5\,\mathrm{min.}}$, $L_{\mathrm{A10},T=5\,\mathrm{min.}}$, $L_{\mathrm{A90},T=5\,\mathrm{min.}}$, *noise climate, noise criterion curves (NC), noise rating curves (NR),* the *balanced noise criterion, preferred noise criterion, room criterion, midfrequency average level, loudness,* and *loudness level*. Statistical results show that among these indices, $L_{\mathrm{Aeq},T=5\,\mathrm{min.}}$ correlates best with the auditory sensation. The second best is *Zwicker's loudness level*, which seems to have been ignored in the setting up of building noise control design guidelines nowadays. Though NC and NR have been widely used in the control of air-conditioning noise spectra and indoor environmental design, their correlations with human auditory sensation are not satisfactory. Their use in predicting human auditory comfort is only marginally acceptable. All other noise indices are found inappropriate for use in noise control for air-conditioned landscaped offices, especially the noise climate and room criterion which actually do not correlate significantly with the human sensation.

As the present investigation was performed in Hong Kong where most office workers are Chinese, it remains to find out whether similar results can be obtained in other cities.

ACKNOWLEDGMENTS

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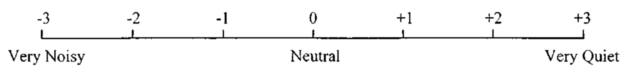
APPENDIX: SCALE FOR AUDITORY SUBJECTIVE RATINGS COLLECTION

The seven-point scale for the collection of the auditory subjective ratings of office workers in the present questionnaire survey is as shown below:



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