NRC Publications Archive Archives des publications du CNRC

Studies of acoustical parameters in open-plan offices Warnock, A. C. C.

This publication could be one of several versions: author's original, accepted manuscript or the publisher's version. /
La version de cette publication peut être l'une des suivantes : la version prépublication de l'auteur, la version
acceptée du manuscrit ou la version de l'éditeur.

Publisher's version / Version de l'éditeur:

Journal of the Acoustical Society of America, 63, 3, pp. 832-840, 1978-03

NRC Publications Record / Notice d'Archives des publications de CNRC:

<https://nrc-publications.canada.ca/eng/view/object/?id=0ba0dbae-33db-4258-a81e-cb3e97ae6e4c>
<https://publications-cnrc.canada.ca/fra/voir/objet/?id=0ba0dbae-33db-4258-a81e-cb3e97ae6e4c>

Access and use of this website and the material on it are subject to the Terms and Conditions set forth at

<https://nrc-publications.canada.ca/eng/copyright>

READ THESE TERMS AND CONDITIONS CAREFULLY BEFORE USING THIS WEBSITE.

L'accès à ce site Web et l'utilisation de son contenu sont assujettis aux conditions présentées dans le site

<https://publications-cnrc.canada.ca/fra/droits>

LISEZ CES CONDITIONS ATTENTIVEMENT AVANT D'UTILISER CE SITE WEB.

Questions? Contact the NRC Publications Archive team at

PublicationsArchive-ArchivesPublications@nrc-cnrc.gc.ca. If you wish to email the authors directly, please see the first page of the publication for their contact information.

Vous avez des questions? Nous pouvons vous aider. Pour communiquer directement avec un auteur, consultez la première page de la revue dans laquelle son article a été publié afin de trouver ses coordonnées. Si vous n'arrivez pas à les repérer, communiquez avec nous à PublicationsArchive-ArchivesPublications@nrc-cnrc.gc.ca.

National Research
Council Canada

Conseil national de
recherches Canada

Canada

Ser
TH1
N2/d
no. 826
c. 2

7026

National Research
Council Canada

Conseil national
de recherches Canada

STUDIES OF ACOUSTICAL PARAMETERS IN OPEN-PLAN OFFICES

ANALYZED

by A.C.C. Warnock

Reprinted from
Journal of the Acoustical Society of America
Vol. 63, No. 3, March 1978
p. 832 - 840

DBR Paper No. 826
Division of Building Research

06257

Price 25 cents

OTTAWA

NRCC 17198

SOMMAIRE

Les principaux éléments acoustiques des bureaux sans cloisons - fenêtres, murs, plafonds et écrans verticaux de séparation - ont fait l'objet d'études en laboratoire avec simulation des problèmes acoustiques qui se posent. Aux fins de l'essai, l'environnement acoustique fondamental consiste en une chambre sourde comportant un plancher en contreplaqué recouvert d'une moquette et sur lequel les éléments d'essai ont été déployés. Les mesures de l'affaiblissement de la transmission du son fourni par diverses configurations ont été effectuées sur une bande de 1/3 d'octave et les données ont été analysées pour permettre d'étudier sept valeurs (à chiffre unique) d'affaiblissement de la transmission du son entre les postes de travail ("atténuation inter-zone"). De toutes les valeurs étudiées, le niveau pondéré A et la Classe d'isolement du bruit correspondaient le mieux à l'indice de netteté, qui est considéré comme étant la "vraie" mesure du rendement. En ce qui concerne la mise à l'essai des plafonds, il a été confirmé que la disposition d'essai des éléments couramment adoptée est insensible aux changements significatifs dans la construction du plafond. On a proposé une simple modification de cette méthode.

Studies of acoustical parameters in open-plan offices^{a)}

A. C. C. Warnock

Division of Building Research, National Research Council of Canada, Ottawa, Canada
(Received 28 February 1977; revised 18 November 1977)

The major acoustical elements of open-plan offices—windows, walls, ceilings, and partial-height screens—have been studied in laboratory simulations of open-office acoustical problems. The basic test environment is an anechoic room with a carpet-covered plywood floor over which the test elements are deployed. Measurements of attenuation provided by various configurations were made in one-third-octave bands and the data processed to permit study of seven single-figure ratings for attenuation between work stations (the “interzone attenuation”). Of the ratings tested the *A*-weighted level and the Noise Isolation Class correlated best with Articulation Index, which is taken as the “true” measure of performance. For testing ceiling systems it is confirmed that the commonly used test arrangement is insensitive to significant changes in the ceiling system. A simple modification of the procedure is proposed.

PACS numbers: 43.55.Gx

INTRODUCTION

Most designers are aware of the important acoustical elements that produce an acoustically successful open-plan office. Many also recognize the importance of considering seemingly small details. The quantitative evidence that has established the importance of these details has not, however, always been placed in the open literature. This paper presents typical results for a variety of problem situations and compares different treatments that attempt to improve matters. Data are used to examine a currently popular test technique and improvements are proposed.

I. MEASUREMENT TECHNIQUES

In all the measurements reported here, only minor variations were made in the techniques used. The experiments were carried out in an anechoic chamber with a carpet-covered plywood floor. A T-bar suspension system for supporting ceiling panels was added when necessary at a height of 2.21 m above the floor (the maximum height available).

Figure 1 shows the positioning of the apparatus. The screen was 1.55 m high, and composed of sections 1.22 m wide. It could be extended the full width of the chamber or reduced in width as necessary. The test signal fed to the loudspeaker was a band of pink noise extending from 100 to 6300 Hz. A microphone 0.9 m (3 ft) in front of the loudspeaker provided reference levels, and measurements were taken at 0.3-m (1-ft) intervals in the range 2.44–3.9 m (8–13 ft) from the loudspeaker. Microphone signals were fed into a General Radio one-third-octave-band filter set and rms detector controlled by a minicomputer that performed all necessary calculations. Two different loudspeakers were used during the experiments. Neither was of very high quality, as shown by the frequency responses in Fig. 2. The off-axis response of these speakers in the range 0°–45° was not uniform for all frequencies. As the investigations

described here were mainly comparisons of different treatments, however, this complication is unimportant.

The output available from the bank of filters included *A*-weighted levels as well as standard one-third-octave-band levels. From these measured levels, interzone attenuations, i.e., attenuations with respect to the reference microphone at 0.9 m, were calculated for all frequency bands, then further reduced in several ways as outlined in Sec. II.

II. REDUCTION OF MEASUREMENTS TO SINGLE-NUMBER RATINGS

In the course of the investigations many measurements were taken, and it was decided to examine several possible single-number methods for rank ordering the systems tested by these procedures. All data were stored in machine-readable form.

When one is concerned with speech privacy, objective measurements may be used in calculations of Articulation Index (AI) performed according to ANSI S3.5.¹ An ideal voice spectrum may be assumed and an arbitrary background-noise spectrum chosen. Speech intelligibility may then be estimated from AI, assuming that the relation between the two quantities is well defined.

FIG. 1. Positioning of apparatus.

^{a)}This paper was presented at 93rd Meeting, of the Acoustical Society of America, Pennsylvania State University, June 1977 [J. Acoust. Soc. Am. 61, S33(A) (1977)].

FIG. 2. Frequency response of loudspeakers used. Sound pressure levels at 1 m on axis.

Bowman² has discussed the development of AI and questioned some of its applications. His experimental data indicate that the relation between AI and intelligibility, obtained by varying masking-sound level, is not invariant but depends on the spectral characteristics of the masking sound, all other factors being held constant.

In contrast, a study by Webster and Klumpp³ of 16 shipboard noises indicates that AI is successful in rating the noises studied. Webster and Klumpp do point out, however, that there seems to be a downward shift in the frequency of central importance as intelligibility is reduced. Young⁴ suggested modified weighting factors to take account of this observation.

Such published data suggest that AI is not uniquely related to speech intelligibility when speech/noise ratios or masking-noise spectra are varied widely. In the open-plan office, however, the spectra of masking sounds that are considered acceptable do not vary widely. As the design objective is to attenuate speech, using screen/ceiling assemblies to produce an acceptable level of privacy in the presence of masking sound, the spectrum of the speech received on the remote side of a screen must also be relatively constant. Under these conditions published information indicates that the AI is the most accurate means currently available of estimating speech intelligibility or, at the very least, changes in speech intelligibility.

Values of AI calculated according to ANSI S3.5¹ depend on voice level and background noise. To avoid this dependence, the standard AI calculations were modified to produce a single-number rating based on measured attenuations only. This is called DAI and is formed as follows:

$$DAI = 30 \times \sum_i A(f_i) w(f_i),$$

where f_i is the center frequency of the bands from 200 to 5000 Hz, $A(f_i)$ is the measured attenuation in the one-third-octave band with center frequency f_i , $w(f_i)$ is the standard AI weighting for that band given in ANSI S3.5.

An examination of DAI ratings so produced shows that, not unexpectedly, they correlate almost exactly with AI values except when AI approaches 0 or 1. This

rating is used as the criterion for assessing the performance of the other ratings examined.

In practice, two rating systems are in common use. The first of these is called NIC', and is defined in the documents of the Public Buildings Service (PBS) of the U.S. General Services Administration.⁵ The NIC' rating procedure is a modification of the standard procedure that gives a Noise Isolation Class (NIC).⁶ NIC' is here identified by the acronym SPNAC₁ (Speech Privacy Noise Attenuation Class) to avoid confusion with the longer-established term NIC.

To derive the SPNAC₁ rating for a particular test, the interzone attenuations for the eight one-third-octave bands from 400 to 2000 Hz, inclusive, are averaged over distance and fitted to the NIC contour in the same frequency range. Adverse deviation is limited to a total of 16 dB and to 4 dB in any single band. This is the requirement given in Ref. 5.

The second common rating is the A-weighted level difference. For this rating the frequency range was determined by the bandwidth of the input signal to the loudspeaker, 100–6300 Hz. The spectrum of the broadcast sound was determined by the loudspeaker frequency response, subject to A weighting.

The complete range of rating systems examined included the following:

DAI—already defined,

ALD₁—already defined,

SPNAC₁—already defined,

SPNAC₂—the same as rating SPNAC₁ (and NIC'), with the 4-dB limitation on maximum adverse deviation removed,

SIL₄—based on Speech Interference Level (SIL)—average attenuation in the four octave bands: 250, 500, 1000, and 2000 Hz,

SIL₃—average attenuation in the three octave bands 500, 1000, and 2000 Hz,

ALD₂—measured one-third-octave-band attenuations are used to calculate A-weighted level differences for a pink-noise source—this effectively removes loudspeaker frequency response effects from consideration,

NIC—Noise Isolation Class as defined in Ref. 6.

Most measurement results are presented in terms of the DAI, SPNAC₁, and ALD₁.

III. REFLECTIONS FROM NEARBY VERTICAL SURFACES AROUND SCREENS

A series of tests was carried out on vertical reflecting surfaces equivalent to windows, walls, and columns. Ceiling reflections were negligible. Reflections from window glass around a screen dividing work areas constitute a particular problem because commonly used window-covering materials such as Venetian blinds or lightweight draperies have a negligible effect on such reflections. A different type of blind is available that one might assume to be an improvement on the Venetian

TABLE I. Configurations of vertical window slats tested.

A	90-mm-wide vinyl slat, 90 mm between centers
B	90-mm-wide slat, 90-mm o.c., perforated vinyl
C	110-mm-wide vinyl slat, 110 mm o.c.
D	Sound-absorbing slats 127 mm wide, 16 mm thick. The surface is uniformly perforated and the interior filled with sound-absorbing material. The NRC obtained when tested according to ASTM C 423 is reported as 0.6.

blind. These blinds have broader, vertically suspended slats. One model has hollow slats filled with sound-absorbing material. Table I lists the selection of blinds tested.

Loudspeaker B was used as the sound source in these measurements and the barrier screen was 2.44 m wide. A vertical (2.44×2.13 m²) hard-reflecting surface was symmetrically placed parallel to the measuring axis and perpendicular to the plane of the extension of the barrier screen to reflect sound around it, simulating a hard wall or window. The distance between the wall, on which specimens were mounted, and the edge of the screen varied. Details are given in the tables where appropriate. A highly absorbing 50-mm-thick glass-fiber ceiling was in place while the measurements in Tables II and III were taken.

Table II lists the mean interzone attenuations obtained for four orientations of the slats. The values for a bare wall and no wall at all are included for comparison. These values are for a source-microphone distance of

TABLE II. Mean interzone attenuations for source-microphone distances of 3.35–3.96 m (11–13 ft) showing effects of angle of slat rotation and type of slat. Measuring axis 1.22 m (4 ft) from the floor. Screen edge 0.71 m from vertical surface.

Surface treatment	Slat angle (deg)	ALD ₁	SPNAC ₁	DAI
No wall		21.7	21	23.4
Bare wall		15.9	13	15.5
Slat type A	0	15.7	10	15.6
	45	15.5	12	16.2
	90	18.25	15	18.3
	135	16.25	12	15.9
Slat type B	0	16.2	13	15.9
	45	15.5	13	16.2
	90	15.5	14	16.2
	135	16	13	16.2
Slat type C	0	16.5	11	16.2
	45	16.25	12	15.9
	90	15.75	12	15.9
	135	16.5	11	16.5
Slat type D	0	19.2	17	19.2
	45	18.2	16	18.6
	90	17.7	15	18.3
	135	18.2	16	18.9

TABLE III. Mean interzone attenuations for source-microphone distance of 3.35–3.96 m (11–13 ft) for some other surface treatments. *H* is the height of the measuring axis. The midplane of the samples was 140 mm from the wall unless otherwise noted.

	ALD ₁	SPNAC ₁	DAI
No wall, <i>H</i> = 1.22 m	21.7	21	23.4
710-mm screen-wall gap, <i>H</i> = 1.22 m			
Bare wall	15.9	13	15.5
110-mm slat, 90 mm o.c.	16	11	16.2
25-mm layer rigid glass fiber in contact with wall	19.25	17	20.7
200% full glass-fiber drapes over bare wall (0.2 kg/m ²)	14.75	12	15
255-mm screen-wall gap, <i>H</i> = 1.22 m			
Bare wall	17	16	17.2
110-mm slat, 90 mm o.c.	18.2	15	18.6
200% full glass-fiber drapes (0.2 kg/m ²)	16.7	15	16.5
255-mm screen-wall gap, <i>H</i> = 910 mm			
No wall	21.5	20	23.1
Bare wall	18	17	17.6
100-mm slat, 90 mm o.c.	19.75	16	19.4

3.35–3.9 m (11–13 ft), the region where specular reflection is worst. It is evident that the orientation of the slats is not important. A single value seems to refute this, but it is ascribed to experimental error. One may also conclude the following: (a) None of the simple vinyl slats produces worthwhile improvement over a bare wall for the screen-wall gap tested; (b) perforations in the slats have no acoustical effect; (c) absorbent slats improve the mean interzone attenuation by about 3 dB, which is useful, but are about 5 dB worse than no wall at all.

Table III lists data obtained under similar test condi-

TABLE IV. Mean interzone attenuations for horizontal slats with and without absorptive treatment. Source-microphone distances 3.35–3.96 m (11–13 ft). Screen 0.91 m from reflecting wall and loudspeaker pointing at wall.

	ALD ₁	SPNAC ₁	DAI
1 No reflecting wall	21.7	18	21.6
2 2.13-m-high $\times$ 1.22-m-wide plywood wall, bare	10.2	7	10
3 25-mm layer of cloth covered rigid glass fiber on wall	17.2	15	18
4 50-mm layer of cloth-covered rigid glass fiber on wall	20.2	18	20.1
5 25-mm layer of glass fiber, spaced 25 mm from wall surface	18.5	17	18.6
6 82-mm-wide slats; midplane 127 mm from wall, 45° to wall surface, 77 mm o.c.	10.2	8	10.5
7 82-mm-wide slats; midplane 127 mm from wall, 45° to wall surface, 150 mm o.c.	10	7	10.2
8 150-mm-wide slats; centerline 127 mm from wall, 45° to wall, 150 mm o.c.	10.2	7	10.2
9 As 8, but 16-mm rigid glass fiber fixed to slats, 150 mm o.c.	14.2	11	14.7
10 As 9, but 230 mm o.c.	14.2	12	14.7
11 As 9, but 300 mm o.c.	13.2	11	13.2

TABLE V. Effect of reducing screen-wall gap on interzone attenuation. Mean for source-microphone distances of 3.35–3.96 m (11–13 ft). The reflecting wall is 2.13 m high $\times$ 1.22 m wide, and the loudspeaker points at the screen.

Test conditions	ALD ₁	SPNAC ₁	DAI
1 No reflecting wall	22.5	19	22.5
2 0.91-m gap	15.7	12	15.3
3 0.61-m gap	13.7	11	14.4
4 0.3-m gap	15.5	13	15
5 0.15-m gap	18	14	18
6 Wall in contact with screen edge	21.7	19	21

tions for several other surface treatments. The following conclusions may be drawn:

(a) For a 0.71-m screen-wall gap, (i) neither slats nor glass-fiber drapes are effective, and (ii) the 25-mm-thick layer of rigid glass fiber improves interzone attenuation over the bare wall by about 4 dB, but the values obtained are still about 3 dB worse than with no wall at all.

(b) For a 0.25-m screen-wall gap, the slats appear to be about 1.5 dB better than a bare surface. This conclusion is not, however, borne out by the SPNAC₁ rating, which differs from the two other ratings. This point is discussed later when correlation of ratings is examined.

The results of a series of experiments investigating horizontal slats are given in Table IV. In this series speaker A was used, no ceiling was installed, the reflecting surface measured 1.22 m wide by 2.13 m high and was 0.9 m from the edge of the barrier screen. The slats were constructed of 5-mm plywood and were mounted so that any reflected sound would tend to be directed upward. The bare slats did not reduce reflections. The addition to the slats of a layer of glass fiber gave some improvement, but there was still a con-

siderable amount of reflected sound compared to the no-wall case.

The effect of varying the gap between the edge of the screen and the vertical reflecting surface can be found in Table V. Clearly, the smaller the gap the less sound reflected around the screen. This suggests that a more effective means of dealing with reflections from windows or walls is simply to use screens shaped to fit closely against them, and to accept the constraints this arrangement places on layout. By extension, this result also implies that the gap between the bottom of the screen and the floor should be eliminated or kept very small; otherwise reflections under the screen will similarly reduce the privacy between work zones.

Tables III and IV show that the application of a layer of glass fiber is an adequate method of dealing with reflections from walls, columns, or large vertical furniture surfaces. Any alternative material should be at least as absorbent. As many carpets do not have high absorption coefficients, wall carpets intended to reduce sound reflection must be carefully chosen.

IV. REFLECTIONS FROM CEILING SYSTEMS

A. Ceiling measurements

It is well established that the most important component in an open office is the ceiling system. Speech sounds are always able to reflect from the ceiling to adjacent work positions. For this reason the greatest part of the testing associated with open-plan offices has been done on ceiling systems. Invariably measurements are made at a height of 1.22 m (4 ft) from the floor to simulate seated speaker and listener. The screen height used is generally 1.52 m (5 ft).

The height differential of 0.3 m (1 ft) between the measurement axis and the top of the screen produces a fixed amount of attenuation between work stations mainly owing to diffraction over the top of the screen. For a typical open-office arrangement this amounts to about

TABLE VI. Description of ceiling samples tested. The absorption coefficients were obtained according to ASTM C 423¹¹ on a No. 7 mounting.

		Absorption coefficients						
		125	250	500	1000	2000	4000	NRC
A	Anechoic chamber ceiling	—	—	—	—	Estimate		1.0
B	50-mm-thick nubby-cloth-faced glass-fiber tiles with impervious back layer	0.41	0.64	1.11	1.15	1.09	1.00	0.9
C	19-mm-thick vinyl-faced glass fiber mounted upside down in T-bar grid	0.55	0.89	0.84	1.04	1.13	1.14	0.95
D	19-mm-thick nubby-cloth-faced glass-fiber tile	0.46	0.88	0.72	0.96	1.05	0.95	0.9
E	19-mm-thick vinyl-faced glass fiber mounted normally	0.55	0.89	0.84	0.99	1.01	0.72	0.95
F	13-mm-thick plywood					Estimate		0.05

TABLE VII. Measured single-figure ratings obtained using six ceiling samples, A-F.

Sample	NRC	SPNAC ₁			ALD ₂			DAI		
		1.22 m	0.91 m	0.61 m	1.22 m	0.91 m	0.61 m	1.22 m	0.91 m	0.61 m
A	1.0	22	26	30	24.1	27.8	31.2	23.4	27.6	31.8
B	0.9	22	23	22	22.5	24.7	24.1	21.9	24.6	24.9
C	0.95	20	20	21	21.9	23.8	24.4	21.3	23.7	24.3
D	0.9	15	17	17	19.4	20.9	21.6	18.9	20.4	21
E	0.95	16	16	17	19.4	20.8	22.3	18.9	20.4	21.9
F	0.05	12	12	13	14.6	15.5	16.4	13.8	15	16.2

20 dB A for a pink-noise signal. When ceilings under test reflect less sound than that diffracted around the screen, then the test is not capable of differentiating between such ceilings. This situation can be improved by reducing the diffracted sound by either increasing the height of the screen or lowering the axis of measurement.

To examine the effects of this change, six samples of ceiling tile were tested using speaker B and a 3.66-m-wide screen extending the full width of the chamber. These ceiling samples are described in Table VI. Table VII lists measured single-figure ratings for the three measuring heights used.

The expected behavior of the single-number ratings was estimated for assumed ceiling reflectivities, constant for all frequencies, in the range 0-1. The excess attenuation A due to diffraction was calculated from the expression⁷:

$$A = 20 \log_{10} [(2\pi N)^{1/2} / \tanh(2\pi N)^{1/2}] + 5 \text{ dB for } N > 0, \quad (2)$$

where $N = 2(A+B-d)/\lambda$, λ is the wavelength of sound, d is the straight-line distance between source and receiver, $A+B$ is the shortest path length of travel over the barrier between source and receiver.

This is an analytical approximation of the experimental data of Maekawa.^{8,9} The calculated diffracted and reflected signals were combined without regard for interference effects. It was assumed that this would give adequate information for the purpose of examining the variations with measuring height. Figure 3 illustrates the calculated behavior of the A -weighted level difference for the three measuring heights used. The other ratings exhibit similar behavior. Table VIII compares calculated and measured values and the range in ratings for the two extreme ceiling samples A and F, reflection coefficient 0 and 1. Agreement between prediction and measurement is surprisingly good. As expected, the range in values is greatest for the survey height of 0.6 m, demonstrating that resolution of this type of measurement can be increased by an optimum measuring height.

Masking-noise levels in the open office are typically about 50 dB A or less. Higher levels tend to provoke occupant dissatisfaction and because of this limitation a ceiling system must achieve SPNAC₁ or ALD₁ ratings

better than 19 for a survey height of 1.22 m if it is to provide acceptable privacy for the office occupants. Figure 3 shows that the average reflection coefficient for such ceilings will be less than 0.2. Consequently, it is in the range of mean reflectivity from 0 to 0.2 that most measurements will be made. Table IX shows the calculated spread in rating values for this range of reflectivity. This suggests that any test with a survey height of 1.22 m (4 ft) and a 1.52-m (5 ft) high screen will probably produce most of its test results within a range of 3 dB. With typical confidence limits of ± 1 dB, such a test cannot accurately rank order highly absorbing ceiling systems, especially when testing is carried out in different laboratories. Nor can it be relied on to reject ceiling systems, again because of the size of the confidence interval.

B. Measurements on light luminaires

Reflections from flat plastic luminaires can seriously reduce interzone attenuation in open offices and it was thought that use of fins to diffuse sound might be an improvement over the flat sheet of plastic. The results presented here are for a very limited examination of two prototypes of finned commercial units. For each of the laboratory tests a single luminaire 1.22 $\times$ 0.3 m² was centered immediately above the screen with its long axis parallel to and directly above the measurement axis. Speaker B was used with a 2.44-m-wide barrier screen. The ceiling comprised 50-mm-thick cloth-covered glass-fiber boards.

FIG. 3. Predicted behavior of ALD₂ for three measuring heights of 0.61, 0.91, and 1.22 m.

TABLE VIII. Comparison of calculated and measured ratings for ceilings A and F, reflection coefficient 0.05 and 1.

Measuring height (m)	Ceiling A			Ceiling F			A-F		
	1.22	0.91	0.61	1.22	0.91	0.61	1.22	0.91	0.61
	SPNAC ₁								
Calculated	20	25	29	19	13	14	8	12	15
Measured	20	26	30	13	12	13	10	14	17
	ALD ₂								
Calculated	21.5	27	30.7	13.1	14.1	15	8.4	12.9	15.7
Measured	24.1	27.8	31.2	14.6	15.5	16.4	9.4	12.6	14.6
	DAI								
Calculated	21.9	27.3	31.2	12.9	14.1	15	9	13.2	16.2
Measured	23.4	27.6	31.8	13.8	15	16.2	9.6	12.6	15.6

The same luminaires were tested in a completed office using identical procedures. Here the luminaires were installed in continuous strips 1.22 m apart on a ceiling composed of 25-mm-thick cloth-covered glass-fiber boards. The screens used as barriers were 1.83 m high and 5.5 m wide. Measurements were made at a height of 1.22 m from the floor. Two axes of measurement were used, one directly under a row of luminaires and one between rows. For comparison, a row of flat plastic sheets was substituted for the finned luminaires in one measurement.

The data are presented in Table X and suggest that the finned plastic units can provide useful improvement over the simple flat sheet of plastic. These measurements may be contrasted with those for slatted-window treatments, which indicated that slats are of no value in reducing specular reflection unless treated with sound-absorbing material. The benefits obtained with the finned luminaires can perhaps be attributed to the narrowness of the reflecting sheets, giving rise to beneficial diffractive effects.

VI. SCREEN TESTING

PBS testing procedures⁵ used to rate ceiling systems and reflecting surfaces are also used to evaluate the effectiveness of screens as barriers and sound reflectors. As the attenuation provided by the screen is determined by diffraction around it, there is no need to measure repeatedly the insertion losses for simple planar screens of similar physical dimensions. They can readily be calculated. It is assumed that the internal structure of the screen attenuates sound to the point where transmission through the body of the screen may be ignored and that reflection under the screen is negligible.

The design of a screen should begin with the specifications of an internal layer to ensure that the screen transmission losses are appreciably higher than the maximum expected diffraction losses at all relevant frequencies. This requirement can easily be satisfied by writing a specification in terms of mass/unit area or sound transmission class.⁶ For example, an internal, impervious layer weighing 2.5 kg/m² (STC > 20) will be quite adequate for screens up to 1.8 m high. The sound diffracted around the screen can then be predicted from Eq. (2). Even where transmission losses through the screen are not high enough, the resulting screen per-

formance can be calculated by combining the diffracted and transmitted signal.

As verification, transmission losses of six plane screens were determined according to ASTM E 90.¹⁰ The screens were then tested using speaker B as the source of sound and with no ceiling installed in the anechoic chamber. The expected levels were calculated, taking account of diffraction at three edges and transmission through the body of the screen. Although not strictly applicable, the measured random incidence transmission losses were used for this calculation. No interference effects were considered. Despite these limitations Table XI shows good agreement for measured and predicted ratings.

The sound-reflective properties of open-office screens are also important. These were estimated by placing a 1.52 × 2.44-m² screen perpendicular to the measuring axis as a barrier. The remaining five screens were placed 0.91 m from the edge of the 1.52 × 2.44-m² screen, perpendicular to its plane and parallel to the measuring axis so as to reflect sound around the barrier. The mean interzone attenuations so obtained are shown in Table XII. Absorption coefficients for the screens were also measured in a reverberation room according to ASTM C 423.¹¹ Noise-reduction coefficients for each screen are listed in Tables XI and XII.

The data in Table IV show that attenuations obtained with a reflecting surface covered by 50 mm of glass fiber are within 1 dB or so of those obtained without reflector. Experience in testing screens in a reverberation chamber according to ASTM C 423 indicates that for an NRC rating of 0.8, or better, this is the approximate thickness that must be used on each side of the inner septum. This value of 0.8 is part of a Canadian specification for screens. All screens with an NRC value of 0.8 or better in Table XII achieve within 2 dB the rating for no reflecting screen. Screen 2 has 25 mm of rigid glass-fiber ceiling board on each side of a 3-mm hard-board septum.

In view of these results, it seems quite adequate to test plane, freestanding screens using E 90 and C 423 rather than the PBS procedures. Good performance in the open office can be ensured by adequate values of STC and NRC and screens large enough to provide the necessary diffraction losses.

Diffraction losses are determined mainly by the height of the screen, typically 1.52 m in open-plan offices. Privacy between work areas can be improved by

TABLE IX. Calculated range in ratings for reflection coefficient in the range 0-0.2.

	Measuring height <i>H</i> in meters		
	1.22	0.91	0.61
SPNAC ₁	3	6	8
ALD ₂	3.5	6.5	9.5
DAI	4.2	7.2	10.0

TABLE X. Interzone attenuations measured for three different plastic luminaires (1.22 × 0.3 m).

	ALD ₁	SPNAC ₁	DAI
Laboratory measurements			
Measuring height = 1.22 m			
Single flat luminaire	16	14	16.3
50 mm fin 75 mm o.c.	16.5	14	17.8
100 mm fin 150 mm o.c.	17.25	16	19.1
Measuring height = 910 mm			
Single flat luminaire	19.5	15	18.9
50 mm fin 75 mm o.c.	20.7	16	21.5
100 mm fin 150 mm o.c.	20.25	18	21.7
Field measurements			
Measurement axis under ceiling tile only	20.25	19	21
Measurement axis under flat luminaire strip	18	15	17.9
Measurement axis under 100-mm fin luminaire strip	20.25	19	21.3

increasing this height, but the office would no longer be quite so open visually. It is perhaps worth pointing out that the top 0.3 m or so of a 1.8-m-high screen could be transparent so as to restore this visual openness.

VII. CORRELATION OF SINGLE-NUMBER DESCRIPTORS

The results of correlating all possible pairs of single-number ratings listed at the beginning of this paper are shown in Table XIII. The values above the diagonal are the correlation coefficients for each pair of ratings. The values below the diagonal are the means of the two standard errors of the estimates obtained for each correlation. This gives an indication of the spread of the data about the regression lines.

Comparing the mean standard errors of the estimates for SPNAC₁ and SPNAC₂, it is clear that the 4-dB limitation on individual adverse deviations associated with SPNAC₁ consistently reduces the degree of agreement with all of the other ratings. This 4-dB limitation appears to have been chosen as a result of halving the 8-dB limitation used in the NIC procedures.

There seems to be no sound basis for this increased restriction. The limitation is usually related to the bandwidth of the measurements, being 8 dB for one-third-octave bands and 5 dB for octave bands.¹² As this limitation was primarily meant to deal with coincidence dips in transmission-loss curves, and as correlation

TABLE XII. Measured interzone attenuations for screen in reflecting position.

Screen	NRC	ALD ₂	SPNAC	DAI
1	0.8	20.4	19	20.1
2	0.67	19.2	17	18.7
3	0.9	19.7	17	19.2
4	0.9	19.7	18	19.2
5	0.95	20.2	19	20.4
No reflecting screen	--	21.1	19	21.3

with the other ratings is improved when it is removed, it is the author's opinion that it should not be used in any open-plan office rating procedure. SIL ratings offer no marked advantages over other ratings and merit no further attention as a method of rating open-office components or systems.

Table XIII shows that DAI correlates well with all ratings and, in particular, that the mean standard error of estimate for the correlation between DAI and ALD₂ or NIC is only about 1/3 dB. Even the ALD₁ rating is as good as the SPNAC₂ rating and better than the SPNAC₁ (NIC') rating.

These measurements of A-weighted level differences were taken with two inexpensive loudspeakers that did not have flat frequency responses, and some of the scatter associated with ALD₁ is caused by the differences between these speakers. It was noted earlier that the SPNAC ratings may indicate that a particular surface treatment is of no value, whereas the ALD or DAI ratings show an improvement of 1 or 2 dB. In some cases part of this difference is due to the 4-dB maximum adverse deviation limitation. In others, the difference arises because of the restricted frequency range used by the SPNAC rating (400–2000 Hz) compared with that of the ALD and DAI ratings.

VIII. MASKING-NOISE DESCRIPTORS

Masking-sound systems are widely used in open-plan offices. The properties of immediate interest are the level, loudness or subjective acceptability of the sound, and its efficiency as a speech masker. PBS-C.2⁵ contains a method of rating masking noises by fitting the

TABLE XI. Measured and predicted ratings for screens tested as barriers.

Screen	Height (m)	Width (m)	NRC	STC	ALD ₂		SPNAC ₁		DAI	
					meas.	pred.	meas.	pred.	meas.	pred.
1	1.44	1.52	0.8	12	17	17.4	15	16	16.8	17.7
2	1.55	1.24	0.67	28	21.2	20	19	18	20.7	20.4
3	1.52	1.52	0.9	15	19.1	19.2	17	17	19.2	19.8
4	1.38	1.51	0.9	11	15.1	16.4	13	15	15.3	16.5
5	1.52	1.52	0.95	20	20.1	19.9	18	18	20.7	20.4
6	1.55	2.49	0.67	28	22	21.1	21	19	21.6	21.3

TABLE XIII. Correlation between ratings. Values above the diagonal are correlation coefficients; values below are means of the two standard errors for each correlation (80 experiments, average of 2.44–3.96 m (8–13 ft) values used in calculations).

Mean standard error of estimate	Correlation coefficients between ratings							
	DAI	ALD ₁	ALD ₂	SPNAC ₁	SPNAC ₂	SIL ₄	SIL ₃	NIC
DAI	...	0.99	0.99	0.98	0.98	0.97	0.98	0.99
ALD ₁	0.64	...	0.98	0.97	0.99	0.98	0.99	0.99
ALD ₂	0.35	0.72	...	0.98	0.98	0.97	0.97	0.99
SPNAC ₁	0.8	1.0	0.88	...	0.98	0.94	0.96	0.98
SPNAC ₂	0.69	0.60	0.81	0.81	...	0.97	0.98	0.98
SIL ₄	0.92	0.80	0.96	1.34	0.91	...	0.99	...
SIL ₃	0.88	0.67	1.0	1.2	0.73	0.50	...	...
NIC	0.33	0.59	0.43	0.82	0.69	...	...	...

spectrum to an NC 40 contour. This is essentially the same as one of the methods used by Klumpp and Webster,¹³ and was shown to be not so effective as Speech Interference Level or Articulation Index methods of rating. The NC 40 method of rating background noise was compared with others by examining the ratings produced for nine masking-noise spectra covering the gamut of those likely to be used in open-plan offices. Table XIV lists the one-third-octave-band levels in each of the nine spectra, all of which had essentially the same A-weighted level (48 ± 0.5 dBA). The other descriptors were SIL₄, SIL₃, and DAI, and were applied to noise levels rather than measured attenuations. Table XV lists the calculated single-figure ratings of the nine spectra, including loudness, calculated according to ANSI S 3.4-1968.¹⁴

With DAI as the reference criterion, Fig. 4 shows the correlation between it and SIL₄, SIL₃, and the NC 40 rat-

TABLE XIV. One-third-octave-band levels of noise spectra examined for masking effectiveness.

Frequency (Hz)	Spectrum number								
	1	2	3	4	5	6	7	8	9
63	61	55.5	49.5	55.5	44	51.5	56.5	41.5	57
80	58.5	54.5	48.5	53.5	44	50.5	54.5	41.5	55
100	56	53	47.5	52.5	44	49.5	52.5	41.5	53
125	54	51	46.5	50.5	44	48.5	50.5	41.5	51
160	51.5	49.5	45.5	49.5	44	47.5	48.5	41.5	49
200	49	48	44.5	47.5	43.5	46.5	46.5	41	47
250	47	45.5	43.5	46	43.5	45.5	44.5	40.5	45
315	44.5	43	42.5	44.5	43	44.5	43.5	40.5	43
400	43	42	41.5	42.5	43	43.5	42.5	40.5	41
500	39.5	41	40.5	41.5	42	42.5	40.5	40.5	39
630	36.5	38.5	39.5	39.5	41	40.5	39.5	40.5	38
800	35	38	38.5	37.5	40	39.5	37.5	41	36
1000	33	36	37.5	36	38	38	36	39.5	35
1250	30.5	33	36.5	33.5	36	35	33.5	38.5	35
1600	29	32.5	35.5	31.5	34	32.5	32.5	37.5	34
2000	26	31	34.5	30	32	30	30.5	35.5	34
2500	24	29	33.5	27.5	31	26.5	29.5	31.5	33
3150	22	28	32.5	25.5	28	22.5	29.5	29	32
4000	19	25.5	31.5	23.5	26	19.5	28.5	26.5	32
5000	17	23.5	30.5	21.5	24	14.5	28.5	20.5	31
6300	14	22	29.5	19.5	20	9.5	27.5	15.5	30

TABLE XV. Single-figure ratings of noise spectra in Table XIV.

Spectrum number	A-weighted level	NC40	SIL ₄	SIL ₃	DAI	Loudness (phons)
1	48.2	3	41.7	38.3	28.2	61.8
2	47.8	2	43.2	40.7	32.7	62.2
3	48	1	43.8	42.3	32.1	61.9
4	47.9	1	43.1	40.5	32.3	61.6
5	47.9	0	43.8	42.4	35.4	60.5
6	48.2	0	43.8	41.6	32.4	60.7
7	47.8	2	43	40.8	31.4	62.1
8	48.2	-1	43.9	43.4	32	59.7
9	48	3	43.2	41	29.8	62.6

ing. All are better than the A-weighted level, which does not differentiate between spectra.

Neither NC 40 nor SIL₃ is really a satisfactory measure of masking efficiency. It can be seen that SIL₄ is slightly superior to the other two, but it is rather insensitive to changes in DAI. SIL₄ was found to be the best of the ratings studies by Klumpp and Webster¹³ also. Figure 5 shows the correlation between loudness and other ratings. In this case only NC 40 predicts loudness reasonably well. The variations in loudness are not so great, however, as the variations in masking efficiency, and loudness is therefore of lesser importance. It is clear that the NC 40 technique for rating background noise offers no advantages over other tech-

FIG. 4. Correlation between methods of rating masking-noise efficiency.

FIG. 5. Correlation between masking-noise rating systems and loudness in phons.

niques easier to use and better known. There seems little justification for continuing its use in the open office.

IX. CONCLUSIONS

Experimental results presented give quantitative estimates of the effects of possible treatments of problem reflections in open-plan offices. Analysis of the results shows that the single number ratings, NIC' and NC 40 used in Ref. 5, are not so successful as simpler, better known descriptors. In particular, *A*-weighted level differences can be measured using a pink-noise test signal with the loudspeaker frequency response made uniform by filters, if necessary. Changing from one-third-octave-band measurements to *A*-weighted level reductions reduces the number of measurements required and greatly facilitates testing. An extended spatial survey, important for complicated systems, would then be relatively easy in either field or laboratory situations.

In the laboratory the well-known NIC contour can be applied to one-third-octave-band measurements of attenuation and good correlation will be obtained with the Articulation Index.

Measurements with a survey height of 1.22 m (4 ft) are quite appropriate if one is concerned with estimating speech privacy in a proposed office system. If the aim, however, is to produce a standardized test of this type that will accurately rank-order ceiling assemblies, then the amount of sound diffracted over the barrier screen should be reduced by lowering the height at which measurements are made.

ACKNOWLEDGMENT

This paper is a contribution from the Division of Building Research, National Research Council of Canada and is published with the approval of the Director of the Division.

¹American National Standard Methods for the Calculation of the Articulation Index," ANSI S3.5 (1969).

²N. T. Bowman, "The Articulation Index and Its Application to Room Acoustics Design," *J. Sound Vib.* **32**, 109-129 (1974).

³J. C. Webster, and R. G. Klumpp, "Articulation Index and Average Curve-Fitting Methods of Predicting Speech Interference," *J. Acoust. Soc. Am.* **35**, 1339-1344 (1963).

⁴R. W. Young, "Re-Vision of the Speech-Privacy Calculation," *J. Acoust. Soc. Am.* **38**, 524-530 (1965).

⁵Method of Test PBS-C.2, Public Buildings Service, General Services Administration, Washington, DC 20405.

⁶"Determination of Sound Transmission Class," ASTM E 413, Am. Soc. Test. Mater., 1916 Race St., Philadelphia, PA 19103.

⁷*Noise and Vibration Control*, edited by L. L. Beranek (McGraw-Hill, New York, 1971), p. 175.

⁸Z. Maekawa, "Noise Reduction by Screens," *Mem. Fac. Eng. Kobe Univ.* **11**, 29-53 (1965).

⁹Z. Maekawa, "Noise Reduction by Screens of Finite Size," *Mem. Fac. Eng. Kobe Univ.* **12**, 1-12 (1966).

¹⁰"Laboratory Measurement of Airborne Sound Transmission Loss of Building Partitions," ASTM E 90, Am. Soc. Test. Mater., 1916 Race St., Philadelphia, PA 19103.

¹¹"Sound Absorption of Acoustical Materials in Reverberation Rooms," ASTM C 423.

¹²"Rating of Sound Insulation for Dwellings," ISO Recommendation R717, p. 6.

¹³R. G. Klumpp and J. C. Webster, "Physical Measurements of Equally Speech-Interfering Navy Noises," *J. Acoust. Soc. Am.* **35**, 1328-1338 (1963).

¹⁴"American National Standard Method for the Computation of the Loudness of Noise," ANSI S3.4-1968.