Frequency Weighting Contours for Predicting the Speech Interfering Aspects of Noise

J. C. Webster

Phil. Trans. R. Soc. Lond. A 1968 **263**, 315-323
doi: 10.1098/rsta.1968.0021

Frequency weighting contours for predicting the speech interfering aspects of noise

By J. C. Webster

U.S. Navy Electronics Laboratory, San Diego, California,
Exchange Scientist at Applied Psychology Research Unit, Cambridge

Introduction

Physical and psychophysical schemes that purported to measure the speech interfering aspects of noise were examined in a series of papers by Klumpp & Webster (1962, 1963) and Webster & Klumpp (1963). Sixteen diverse-spectrum noises were adjusted in level so that listeners hearing monosyllabic (rhyme) words at a constant level of 78 dB from a loudspeaker obtained 50 % word intelligibility scores. Articulation index (a.i.) calculations (see Kryter 1962*a*) predicted the speech-interfering properties of the noises very well. However, other, and simpler, schemes worked just as well; for example, speech interference level (s.i.l.) calculations (see Beranek 1954), based on octaves centred at 425, 850 and 1700 Hz, or 500, 1000 and 2000 Hz. The A-weighting and Din 3 networks (see Peterson & Bruel 1957), of a sound level meter (s.l.m.) were good, but the conventional use of noise criteria (n.c.), or alternate noise criteria (n.c.a.) (see Beranek 1957), curves did not work well unless (1) only that part of the curves centering on the octaves 500, 1000 and 2000 Hz was used, and (2) the noise spectra were allowed to 'average through' a contour and not just touch it at a peak value.

In the process of trying all possible noise-rating schemes, it became evident that there were essentially three basic ways to rate the speech interference properties of noises. And although the three basic methods differ in how they operate, the best of each method was pretty good and with a few compromises here and there the three basic simple methods might become quite comparable.

Methods of rating speech interference

The three basic methods of rating the speech-interfering properties of noise are: (1) average-level methods (the a.i. being the most comprehensive, universal, and the best predictor, but the s.i.l. doing as good a job if the proper octaves are chosen initially); (2) s.l.m. frequency weighting networks (A and Din 3 being conclusively better than either B or C); and (3) tangent-to-curve methods. The simplest in concept, but the worst in predictive ability, is the tangent-to-curve method. In this method, only the noise component (peak) that first touches a generalized noise-rating contour determines the rating. Any pure tone component, or any restricted band component, that differs drastically from its surroundings dominates this rating.

The tangent-to-curve method may be expressed mathematically as follows:

$$\text{n.r.} = 10\log_{10}\{k(f,p)\,p_m^2/p_0^2\}, \tag{1}$$

where n.r. is any noise-rating criteria desired such as n.c., n.c.a., or i.s.o.; and k is a frequency- and sound-pressure-dependent weighting factor (represented by families of n.c., n.c.a., or i.s.o contours; p_m is the maximum sound pressure (the noise spectral peak that first touches a given contour); and p_0 is a reference sound pressure (usually 0·0002 μbar). The magnitude of n.r. is the logarithm of the weighting factor at the frequency of p_m and the maximum noise-sound pressure.

For the weighted integration (s.l.m. or network) method, the indicating instrument following the weighting network in a s.l.m. adds components powerwise, i.e. two equal components result in a level 3 dB greater than either level individually; nevertheless, as in the tangent-to-curve method, a single component 10 dB greater than all its neighbours essentially determines the level. The frequency weighting network can be expressed mathematically as follows:

$$w = 10 \log_{10}\{\Sigma[k_1(f, p)p_1^2 + k_2(f, p)p_2^2 + \ldots + k_n(f, p)p_n^2]/p_0^2\}, \tag{2}$$

where w is a sound-level weighting reading; k_1 is a frequency-dependent weighting factor determined by the definition of w; $p_1 \ldots p_n$ are sound pressures in contiguous bands. The magnitude of w is the logarithm of weighted sums of squared band sound pressure.

The average-level methods (a.i. and s.i.l.) work conversely. Whereas the tangent and network methods are determined by one (tangent) or more (network) sound pressure peaks and give readings equal to (tangent) or greater than (network) the highest peak sound pressure level, the average-level methods yield measures lower than any single peak by the inclusion of lower levels.

The average-level method can be expressed mathematically as follows:

$$\text{s.i.l.}_{1-n} = 10 \log_{10} \{[k_1(f, p)p_1^2 \times k_2(f, p)p_2^2 \times \ldots\, k_n(f, p)p_n^2]^{1/n}/p_0^2\}, \tag{3}$$

where s.i.l.$_{1-n}$ is a speech interference level of n bands, both the number, and the location, of the bands must be specified; k is a frequency and sound-pressure level dependent weighting factor (but for s.i.l. calculations in the past, k_1 has been equal to $k_2 \ldots k_n = 1$); $p_1 \ldots p_n$ are sound-pressure levels in specified bands. As a consequence of the properties of logarithms an equivalent s.i.l. result can be obtained by taking the arithmetic mean of the levels and adding a constant which will depend on the weighting—a process less involved than taking the individual differences and averaging, but a process that can be used only if k is neither zero nor a function of p; i.e. all s.i.l. differ by constants. The magnitude of an s.i.l. is the logarithm of a product of weighting factors plus the logarithm of a harmonic mean of band sound pressure.

As an example of how these three methods differ, consider a noise that did not deviate at all from some fixed-frequency-weighting function (such as the A-level network in sound-level meter and its equivalent contour for the other two methods). If the deviation of the noise level from the weighting function was 0 dB in each of four pertinent octave bands, then, by the average level and the tangent-to-curve methods the deviation would be 0 dB; and by the integration method the deviation would be 6 dB. A tonal component deviating +10 dB from the weighting functions in one band would cause a deviation of +2·5 dB by the average level method, of +11·1 dB by the integration method, and a deviation of

10 dB by the tangent-to-curve method. Two 10 dB tonal components in adjacent octaves would increase the average level by 5, the integration-method reading by 13·4, and the tangent rating by 10. Two 10 dB tonal components in the same band would increase the average level by 3·3, the integration level by 13·6, and the tangent rating by 13. Licklider & Guttman (1957) have shown that tonal components do not mask speech very effectively so the speech interference properties of these four hypothetical noises would be approximately equal.

To summarize the example: the deviation of average-level measures on these hypothetical noises varied from 0 to 5, the integrated levels showed deivations of 6 to 13, and the tangent ratings deviated from 0 to 13. The weighted 5-octave band a.i. would act much as the same as the average-level measure except that weighted averages would be involved and, in fact, in the examples above, changes in a.i., expressed in dB, could be as large as 5·9, depending on which octaves the two tones were in and whether the level of speech kept the speech/noise (S/N) within the 0 to 30 dB range. To express a.i. in dB, recall that an a.i. of 0 corresponds to an average S/N differential of 0, a.i. of 1 corresponds to a 30 dB S/N, an a.i. of 0·5 to 15 dB, etc., so any value of a.i. can be expressed as some S/N between 0 and 30.

It follows from the above discussion that on any given noise the integration methods will give the highest numerical ratings (two equal peaks together add 3 dB), the tangent-to-curve method next (highest peak, or peaks, determines rating, no summing), and the averaging methods the lowest ratings. This is strictly true only if the frequency-weighting networks have the same general shape for frequency against level as the inverse of the tangent-to-curve rating contours.

Since the A network is very similar in shape to the inverse of the n.c. and/or n.c.a. contours, it is not surprising that the ratings assigned to the sixteen equally speech-interfering noises in table 2 of Klumpp & Webster (1962) are higher in magnitude on A weighting (83·5 dB) than on n.c.a. curve-limiting (78·7 dB), and that both are larger than the s.i.l. (73·7 dB). (These data are reproduced in columns 5, 8, and 13 of table 1.)

The absolute magnitude of the ratings assigned by variants of the three basic methods is not, however, the most important facet. It is the dispersion (standard deviation) of the ratings assigned to the sixteen equally speech-interfering noises that is important. The lower the standard deviation the better the method measures the speech interfering aspects of the sixteen noises.

PURPOSE

It is the purpose of this paper to construct a speech interference (s.i.), frequency-weighting curve that can be used: (1) to calculate a weighted s.i.l., (2) as a filter in a s.l.m., and (3) as a substitute for the n.c. type (n.c., n.c.a., and i.s.o.) contour at the 70 dB level. The curve will be designed to measure only the speech-interfering properties of noises. To the extent that speech interference is the determining factor in the judged loudness, annoyance, or office environment acceptability, this speech interference contour will measure that quantity.

Specifically, a contour will be developed that reduces the dispersion among the ratings of the sixteen equally speech-interfering noises reported by Klumpp & Webster (1963).

The purpose will be to devise methods and means of better estimating the speech-interfering properties of noise without using the more involved a.i. technique.

From this basic contour a set of contours will be developed to bridge the gap between it and Beraneks n.c. and n.c.a. contours for rating office acceptability.

SPEECH INTERFERENCE

On the basis of the results of Klumpp & Webster (1963), the guide-lines for developing a speech interference contour at the noise and speech levels used for those studies are clear. For 50 % scores in relatively high-level noises (as compared to acceptable offices), the frequency regions of the noise that limit the speech are centred at 500, 1000, and 2000 Hz. If the speech interference contour is to be used as a filter network in a sound level meter, sound of frequency below 300 Hz and above 3000 Hz must be discriminated against. Likewise, when used as a tangent-to-curve determiner the same frequency cutoffs must be observed. When used a as shaping network for calculating an s.i.l. or average-curve-fitting within the octaves 500, 1000 and 2000 Hz, the centre octave needs to be emphasized somewhat more than the others.

With these general guide-lines a contour labelled s.i. 70 was developed as shown in figure 1. Using this s.i. 70 contour, the sixteen equally speech-interfering noises were rated as detailed in table 1. All of the ratings in table 1 (except those in italics which are taken directly from Klumpp & Webster (1963) are calculated measures, including those where it is assumed that the inverse of the s.i. 70 (and labelled 'A′') is used as a filter network in a s.l.m.

In columns 1 and 2 of table 1 are listed the numbers, and names, of the sixteen noises. For comparison reasons the C and A weighting network ratings from Klumpp & Webster (1963) are shown in columns 3 and 5, the n.c.a. and i.s.o. (R) ratings in columns 8 and 9, and the 3-band s.i.l. in column 13. In column 4 is the rating that would result if a flat (C) weighting were used in a s.l.m. but bandpassed to include only the octaves centred at 500, 1000, and 2000 Hz. This column is labelled C(R); the 'R' specified here, as elsewhere in the table, signifies 'restricted range'.

The remaining columns in table 1 are ratings the sixteen noises would get if the s.i. 70 curve were used as a new A network, namely A′; for the whole frequency range (column 6) or A′(R) for the restricted range. Column 10 lists results from using the s.i. 70 contour as the curve for the tangent-to-curve method. In column 12 are given the measures of the s.i. 70 curve when used as an averaging curve to find a 5-octave s.i.l. (based on centre frequencies of 250, 500, 1000, 2000 and 4000 Hz). In column 14 are the results of restricting this averaging procedure to the usual restricted band (500, 1000 and 2000 Hz).

Below each column are two measures of dispersion: the range (highest minus lowest rating) and the standard deviation; and the mean rating on the sixteen noises. The rank order refers to the relative smallness of the standard deviation. The smaller the standard deviation the better is that method in rating the noises to be, as they have been adjusted to be, equally speech-interfering. By comparing the standard deviations on table 1 it is evident the new contour does what it was designed to do. It provides a single curve which as far as predicting the speech-interfering properties of relatively high levels of noise;

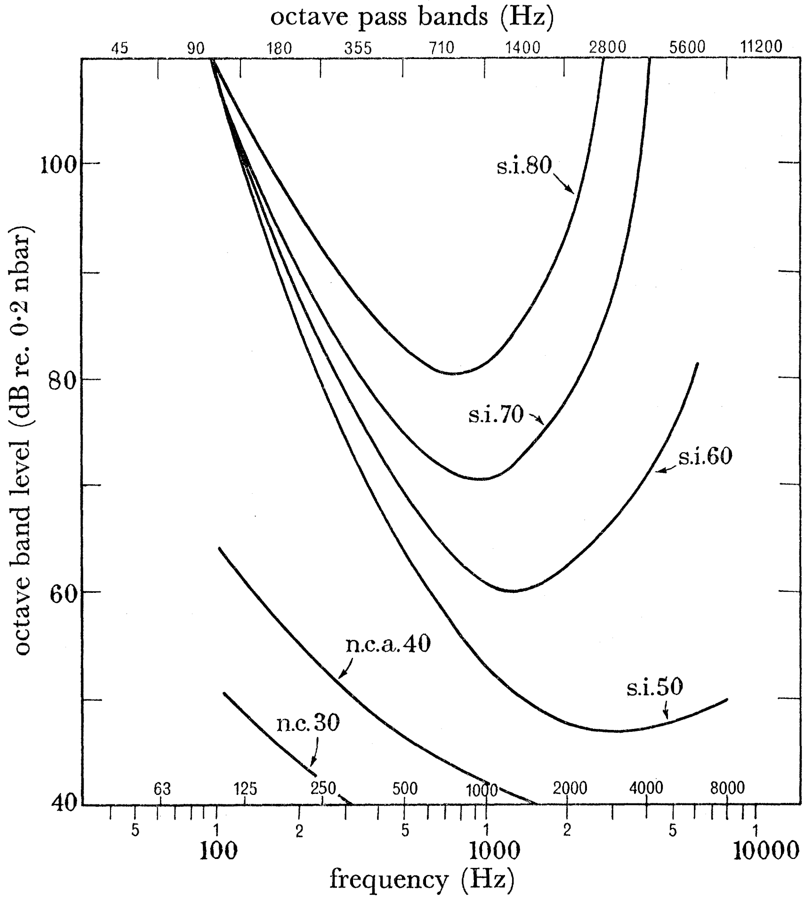

Figure 1. Speech interference noise-rating contours.

Table 1. Variability associated with various measurement procedures

1	2	3	4	5	6	7	8	9	10	11	12	13	14
		weighting networks					tangent-to-curve				averaging or s.i.l.'s		
	noise	C	C(R)	A	A′ 70	A′(R) 70	n.c.a. 70	i.s.o. (R)	n.c.A′ 70	phons	A′ 70	3-band	A′(R) 70
(1)	ship rumble	*105·3*	80	*86·3*	79	76	*80*	*77*	75	100	64	*71·6*	68
(2)	grab eng.	*97·6*	83	*86·3*	81	79	*81*	*80*	78	97	63	*71·1*	68
(3)	blower	*92·3*	84	*85·1*	81	79	*79*	*82*	78	94	64	*73·7*	70
(4)	TN-6	*86·8*	78	*79·3*	77	76	*73*	*74*	72	89	62	*73·1*	70
(5)	blower and hull	*85·3*	79	*78·8*	76	75	*73*	*75*	73	89	56	*72·3*	69
(6)	shear	*78·8*	74	*75·8*	73	72	*69*	*71*	67	86	59	*68·5*	66
(7)	generator	*79·3*	75	*78·6*	72	72	*72*	*74*	68	88	60	*69·6*	66
(8)	compressor	*81·0*	77	*78·5*	74	74	*73*	*74*	71	90	62	*72·0*	69
(9)	babble	*80·3*	79	*80·8*	77	77	*76*	*77*	74	87	61	*74·8*	71
(10)	TN flat	*80·7*	80	*81·6*	76	76	*78*	*80*	72	94	62	*72·6*	69
(11)	arresting gear	*85·3*	82	*83·8*	80	80	*78*	*79*	76	93	66	*77·3*	74
(12)	engine room	*86·3*	84	*84·3*	82	82	*78*	*81*	79	92	66	*77·4*	74
(13)	air grinder	*84·3*	80	*84·8*	77	77	*84*	*82*	73	96	64	*75·3*	72
(14)	typewriter	*86·4*	82	*87·4*	79	79	*85*	*83*	75	97	65	*74·8*	71
(15)	TN + 6	*88·3*	84	*89·8*	80	80	*85*	*87*	79	98	65	*75·9*	72
(16)	jet	*93·8*	89	*94·3*	82	82	*94*	*90*	81	106	70	*79·0*	76
	range	*26·5*	15	*18·5*	10	10	*25·0*	*19·0*	14	20	14	*10·5*	10
	mean	*87·0*	80·6	*83·5*	77·9	77·3	*78·7*	*79·1*	74·3	93·5	63·1	*73·7*	70·3
	std	*7·4*	3·7	*4·7*	3·0	3·0	*5·2*	*4·8*	3·7	5·2	3·2	*2·8*	2·8
	rank	*8*	4	*5*	2	2	*7*	6	4	7	3	*1*	1
	group	*4*	2	*3*	1	1	*3*	*3*	2	3	1	*1*	1

(1) makes a better filter network than the A weighting, (2) makes a better noise rating curve than the n.c., n.c.a. and i.s.o. curves, and (3) can be used as an averaging curve to find an s.i.l. that is equivalent to the 3-band preferred frequency s.i.l.

The next task is to generalize this single contour into a set of contours at higher and lower decibel levels. Ideally, these contours will extend the upper range of Beranek's (1957) noise criteria (n.c.) and alternate noise criteria (n.c.a.) curves for rating '...the maximum noise level at which office personnel feel they can accomplish their duties without loss of performance'. Working spaces exist that exceed Beranek's (1957) maximum contour (n.c. or n.c.a. 70) and that very often exceed his recommended maximum of n.c. 55. The rationale for developing these contours is that in certain spaces, certainly some shipboard areas, noise levels exceed n.c. 55 but work must and does continue, including voice communications. In these areas the major criterion must be acceptable speech intelligibility with little or no regard for loudness, annoyance, or comfort. To rate these spaces, therefore, contours based on comfort and speech communication performance must drop the comfort (loudness and annoyance) and base the rating and eventual acceptance only on those aspects of noise that affect speech intelligibility.

The contours will be developed by utilizing the results of an extensive literature survey of the effects of noise and frequency bandwidth on speech intelligibility (see Webster 1964).

The generalizations from the literature as summarized by Webster (1964) are: speech frequencies below about 350 Hz and above 3900 Hz are relatively unimportant to the intelligibility of speech in noise (Egan & Wiener 1946; Kryter 1960; Pollack 1948); according to Dreher & Evans (1960–61), noise frequencies below 300 Hz are very ineffective in masking speech at tolerable listening levels unless higher noise frequencies are also present; according to Miller (1947), noise bands above 2400 Hz are very ineffective in masking speech; Kryter (1960) states that the most important narrow bands of speech energy are centred at 500 (to 750 Hz), 1750 ± 250 Hz, and 2500 (to 3000 Hz); Kryter (1962*b*) also states that any decrease in speech bandwidth in the 1200 to 2400 Hz band reduces intelligibility; the most important mid-frequency in broad-band speech, according to Egan & Wiener (1946), is somewhere between 1100 and 2000 Hz and the bandwidth required for high intelligibility is about 3·5 octaves; Egan & Wiener (1946) also state that at good speech/noise conditions (at high levels of speech intelligibility) the important broad-band centre frequency is around 2000 Hz and frequencies as high as 6500 Hz may be important; as the speech/noise conditions deteriorate, the important mid-frequency shifts down to around 1000 Hz and frequencies above 3900 Hz are ineffective (Egan & Wiener 1946; Kryter 1960; Pollack 1948; Dyer 1962).

The remaining speech interference (s.i.) contours (s.i. 50, 60 and 80) in figure 1 were drawn relative to the s.i. 70 contour on the basis of the above observations, which are quantitative as regards frequency but only qualitative as regards sound pressure levels. The s.i. contours show: (1) a gradual shifting from a minimum of 800 Hz for s.i. 80 to 2000 Hz for s.i. 50, (2) an increasing disregard of high-frequency noise components from n.c.a. 40 through s.i. 50, 60 and 70 to s.i. 80, (3) a sudden disregard of low-frequency noise components from n.c.a. 40 to s.i. 50, then increasing concern for low-frequency noise for the contours s.i. 60, 70 and 80. These contours are developed on the basis that for levels of noise below the n.c. 30 contour, comfort, annoyance, and purely aesthetic values govern the use of a room. At n.c.a. 40, Beranek (1957) states that all due allowance is made for the difference between loudness and speech interference, and above n.c.a. 40 the environment is admittedly adverse and speech interference alone is hypothesized to be the determiner of acceptance.

In this regard it is interesting to note that in specifying the comfort of aircraft cabins (propeller-driven), Lippert & Miller (1951) define as 'ideally quiet' a noise spectrum that becomes tangent to the s.i. 70 contour (between 500 and 1000 Hz). This spectrum is at least 15 dB above Beranek's (1957) n.c.a. contour of 55 which he describes as 'Very noisy; office environment unsatisfactory;... not recommended for any type of office'. Here is a case, and there are others, where the adaptability level of humans comes to their aid. A noise level that makes offices 'unsatisfactory' is 15 dB less intense than a noise judged to be 'ideally quiet' in airplane cabins. Lippert & Miller (1951) define a second contour exactly 20 dB higher as 'quasi-comfortable. This latter level is 35 dB above Beranek's 'unsatisfactory office'.

It is this adaptability feature of human behaviour that gives rise to the rationale behind the discontinuity in the contours between n.c.a. 40 (where comfort is of importance) and s.i. 50, and on through the s.i. 60, 70 and 80 contours, where the important aspect of the noise is its speech interference properties, not its loudness, its annoyance, nor its habitability and comfort properties.

One way of looking at the speech interfering properties of noise has just been summarized. A set of contours has been developed which weight the spectral regions at various levels of noise that interfere with speech intelligibility. This was treated in some detail because parts of it have only been previously reported in a government report (Webster & Klumpp 1965) not easily available in the open literature.

A second way of looking at the problem is to take one measure of noise and show the relative intelligibility of speech as the noise level increases. This has been reported before in the *Journal of the Acoustical Society of America* (Webster 1965) and will be treated lightly here, since the details are easily available elsewhere.

Figure 2 is a generalized summary of the scope of communicating by speech in noise: on the ordinate is plotted percentage of rhyme words heard correctly and along the abscissa is the level of noise.

The choice of the 0·5/1/2 s.i.l. of an equivalent −6 dB/octave thermal noise is based on two facts. The first is that the 0·5/1/2 s.i.l. is a reasonable compromise for showing small numerical fluctuations among the physical measurements of the original sixteen equally speech-interfering noises. The second is that the −6 dB/octave noise is a reasonable compromise among noises representative of ship noises, office noises, and noises used in laboratory studies of speech intelligibility.

Figure 2 deals with three specific communication situations: face-to-face, sound-powered phone, and amplified speech. It shows for each form of communication the limiting noise levels for given degrees of communication effectiveness (percentage of rhyme words correct). For the majority of the studies summarized in figure 2, a single experienced talker and five experienced listeners were used.

The limiting factor in face-to-face communication in noise is the distance between the talker and the listener, since the potential voice level of the talker and acceptable listening levels are physiologically limited. Observe in the four curves to the left in figure 2 that at any single criterion level, say 70 % correct, for each doubling of the distance between talker and listener, 6 dB less noise can be tolerated.

When the same five listeners and the same talker used in the face-to-face experiment are tested on sound powered phone (s.p.p.) equipment, the s.p.p. results summarized in the centre of figure 2 obtain. With present-day operational, non-noise-proofed phones, the results are no better than face-to-face communication at, say, 2 ft. (considering the 70 % criterion). However, 'developmental' equipment utilizing noise-cancelling microphones and noise-attenuating cushions around earphones does extend usable communications to noise levels beyond face-to-face capabilities.

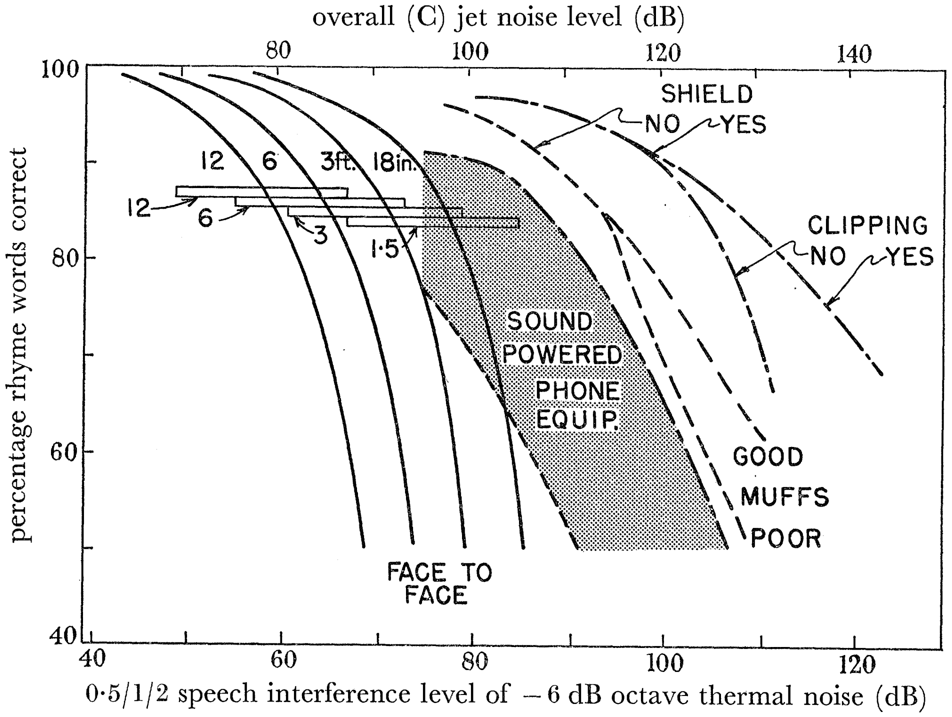

FIGURE 2. Speech intelligibility (percentage rhyme words correct) as a function of jet-aircraft idling noise level. On the top abscissa, noise levels are listed as measured on the C-weighting network of a sound-level meter. On the bottom abscissa, the noise level is listed as the speech interference level (s.i.l.) based on the octaves centred at 500, 1000 and 2000 Hz, of a −6 dB/oct shaped thermal noise that is equivalent in its ability to interfere with the intelligibility of speech to the jet-noise levels listed on the top abscissa. Three generic of results are shown: face-to-face, sound-powered phone, and amplified speech. Within the face-to-face results, the parameter is distance between talker and listener. The limits on the sound-powered results are present-day 'operational' equipment (to the left) and 'developmental' equipment (to the right). In the amplified-speech results, the major parameter is presence or absence of a microphone shield. When a shield is used, a subparameter is whether or not clipping is used for earphone listening. When a shield is not used, the subparameter is whether an average (left) or excellent (right) earmuff is used around the earphone.

When the noise level is too great for face-to-face or s.p.p. communications, amplification is needed, the parameters are: whether a shield is used around a noise-cancelling microphone (shield; yes–no); whether good sealing earmuffs are used; and finally whether peak clipping is used. Using all of the best at the present state of the art, 70 % word intelligibility, which is adequate for most communication systems, can be achieved at an s.i.l. of 120 dB of -6 dB per octave noise (or its equivalent 143 dB of jet noise measured with the C weighting network of a sound level meter).

In summary the speech-interfering aspects of noise are dependent upon both the level and spectrums of the noise components such that there is (1) an increasing disregard for high-frequency noise components as the noise increases from levels of 40 to 80 dB (as estimated by an A-weighting network of a sound level meter), (2) a sudden disregard of low frequency noise components as the noise level passes 60 dB (A) and an increasing concern again for A levels above 80 dB, and (3) a shifting of the major concern for noise components centred at 2000 Hz for A levels of 40 dB and below to components centred at 1000 Hz and below in noises with A levels of 70 dB and above.

REFERENCES (Webster)

Beranek, L. L. 1947 The design of speech communication systems. *Proc. Inst. Radio Engrs* **35**, 880–890.

Beranek, L. L. 1954 *Acoustics*, pp. 419–420. New York: McGraw-Hill.

Beranek, L. L. 1957 Revised criteria for noise in buildings. *Noise Control* **3**, no. 1, 19–27.

Dreher, J. J. & Evans, W. E. 1960–61 Speech interference level and aircraft acoustical environment. *Human factors*, **2**, 18–27.

Dyer, W. R. 1962 The masking of speech by high- and low-pass noise. *Tech Doc. Rome Air Devel. Centr.* no. RADC-TDR-62-298.

Egan, J. P. & Wiener, F. N. 1946 On the intelligibility of bands of speech in noise. *J. acoust. Soc. Am.* **18**, 435–441.

Klumpp, R. G. & Webster, J. C. 1963 Physical measurements of equally speech-interfering Navy noises. *J. acoust. Soc. Am.* **35**, 1328–1338.

Klumpp, R. G. & Webster, J. C. 1962 Predicting speech interference from physical and psychophysical measures of ambient noise. *Proc. Communication Seminar, Stockholm, Sweden.*

Kryter, K. D. 1960 Speech bandwidth compression through spectrum selection. *J. acoust. Soc. Am.* **32**, 547–556.

Kryter, K. D. 1962*a* Methods for the calculation and use of the articulation index. *J. acoust. Soc. Am.* **34**, 1689–1697.

Kryter, K. D. 1962*b* Validation of the articulation index. *J. acoust. Soc. Am.* **34**, 1698–1702.

Licklider, J. C. R. & Guttman, N. 1957 Masking of speech by line-spectrum interference. *J. acoust. Soc. Am.* **29**, 287–296.

Lippert, S. & Miller, M. H. 1951 An acoustical comfort index for aircraft. *J. Acoust. Soc. Am.* **23**, 478.

Miller, G. A. 1947 The masking of speech. *Psychol. Bull.* **44**, 105–129.

Peterson, A. & Bruel, P. V. 1957 Instruments for noise measurements. Pp. 16–13 and 16–14 in Harris, C. M., *Handbook of noise control*. New York: McGraw-Hill.

Pickett, J. M. & Kryter, K. D. 1955 Prediction of speech intelligibility in noise. *Air Force Cambridge Res. Centr. Tech. Rep.* no. 55–4.

Pollack, I. 1948 Effects of high-pass and low-pass filtering on the intelligibility of speech in noise. *J. acoust. Soc. Am.* **20**, 259–266.

Webster, J. C. 1964 Generalized speech interference noise contours. *J. Speech Hearing Res.* **7**, 133–140.

Webster, J. C. 1965 Speech communications as limited by ambient noise. *J. acoust. Soc. Am.* **37**, 692–699.

Webster, J. C. & Klumpp, R. G. 1963 Articulation index and average curve-fitting methods of predicting speech interference. *J. acoust. Soc. Am.* **35**, 1339–1344.

Webster, J. C. & Klumpp, R. G. 1965 Speech interfering aspects on Navy noises. *U.S. Navy Electronic Lab. Rep.* no. 1314.