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Regulation of Voice Communication by Sensory Dynamics

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People speak more loudly in a noisy room or when momentarily deafened and more softly in a quiet room or when sidetone is artificially increased. The effort to compensate for these changes in the signal-to-noise ratio, or to match directly changes in the intensity of a model, typically falls about halfway short (in decibel units). This is probably because a speaker considers that he has doubled his own vocal level in half as many decibels as it takes to double the loudness of the signal or the noise. More concisely, the Lombard-reflex, sidetone-penalty and cross-modality matching functions have exponents of about one-half because the exponent of the loudness scale is half that of the autophonic scale of voice level. This amounts to saying that the speaker matches changes in signal or in noise to keep the signal-to-noise ratio nearly constant, but he is misled by the disparity in the sensory operating characteristics of speaking and listening.

For a subject to perceive a doubling in loudness, the sound-pressure level must be more than tripled if generated by an external source, but less than doubled if generated by the subject himself, vocally. The former relation is well known as the *sones scale* (Stevens¹); the latter is becoming known as the *autophonic scale*, a term coined in the pages of this JOURNAL by Lane, Catania, and Stevens,² who described the speaker's perception of his own vocal level in some detail.

When a speaker judges the dynamic characteristics of his own speech, the possible sources of cues include airborne sound (air sidetone), head sidetone, and proprioception. When the speaker stops talking and listens to someone else instead, he is deprived of most of these cues and, as a listener, he must base his judgments differently. Since the sensory characteristics of speaking and listening are so different structurally (von Békésy³), it is not surprising to learn that they are quite different functionally. After establishing that the exponent (slope, in log-log coordinates) of the autophonic scale is approximately 1.2 whereas that of the sones scale is 0.6, Lane, Catania, and Stevens went on to confirm this disparity by asking subjects to match their vocal levels to changes in the level of a criterion sound. Given

that $A = P_s^{1.2}$ and $L = P_c^{0.6}$ (where P_s and P_c are changes in pressure level, A and L are the corresponding changes in subjective magnitude, and constants governing the size of units are ignored), if A and L are equated at various levels, it follows that the matching function will be $P_s^{1.2} = P_c^{0.6}$, or $\log P_s = 0.5 \log P_c$.

This is simply an application of the method of cross-modality validation, which has been used many times to verify the relations among the exponents of the power functions governing different sense modalities.⁴ In this case, the predicted outcome was surprising: since loudness grows about half as fast as autophonic level, a listener presented with a fourfold increase in sound pressure will match it with only a twofold increase in his vocal level. In other words, the 1:2 disparity between the exponents (slopes) of the sones and autophonic scales yields a matching function that is linear in decibel coordinates with a slope of one half. The slopes obtained were 0.51 and 0.52 in two experiments.

In complementary experiments, speakers were instructed to compensate for, rather than match, the changes in the loudness of a criterion sound, so that the loudness would be held constant. The criterion sound was the speaker's own voice, fed back to him at various levels in an interphone system, and his task was to vocalize so as to compensate for changes in amplification introduced into the sidetone channel. Again the

¹ S. S. Stevens, "The Measurement of Loudness," *J. Acoust. Soc. Amer.* **27**, 815-829 (1955).

² H. L. Lane, A. C. Catania, and S. S. Stevens, "Voice Level: Autophonic Scale, Perceived Loudness, and Effects of Sidetone," *J. Acoust. Soc. Amer.* **33**, 160-167 (1961).

³ G. von Békésy, *Experiments in Hearing* (McGraw-Hill Book Co., New York, 1960), pp. 128-147; 181-203.

⁴ J. C. Stevens, J. D. Mack, and S. S. Stevens "Growth of sensation on Seven Continua as Measured by Force of Handgrip," *J. Exp. Psychol.* **59**, 60-67 (1960).

results confirmed the disparity in the underlying sensory operating characteristics. Since loudness grows about half as fast as autophonic level, a speaker presented with a fourfold increase in sidetone will restore his original loudness, as he perceives it, by halving his vocal level. In other words, the sidetone-compensation function is the complement of the matching function; both have slopes whose absolute value is about one-half. The obtained slope for the sidetone-penalty function (as telephone engineers call it) was -0.46 .

In 1911 the French otorhinolaryngologist Lombard described qualitatively a third relation between the dynamics of listening and speaking.⁵ Lombard observed that when he engaged a patient in ordinary conversation and then presented an intense noise, the patient would immediately increase his vocal level. When the noise stopped, the patient would lower his voice to its former level. Neither change seemed to be conscious. Lombard then carried out a skillful series of parametric studies that showed how the Lombard reflex, as it has come to be known, could be used in audiological examination especially in cases of malingering, for which it is used to this day (Moulouguet,⁶ Fournier⁷).

It is natural to ask whether the Lombard reflex also is governed by the mismatch in the dynamics of speaking and listening. Lombard believed that the increase in voice level caused by increased ambient noise and the increase caused by reduced sidetone (which he observed in patients with nerve deafness) were related phenomena:

Un sujet élève anormalement la voix au milieu d'un vacarme intense . . . Tout se passe comme si le sujet était momentanément dans les conditions d'un malade dont l'audition est abaissée.⁸

This statement suggests that the Lombard-reflex function and the sidetone-penalty function are complements; noise compensation, like sidetone compensation and matching, may be expected to go only halfway (in decibel units). Performance on all three tasks would then confirm the descriptions of the underlying sone and autophonic scales.

⁵ Lombard's research conducted in 1909 at the Hôpital Lariboisière was reported orally to the French academy of Medicine on 4 October 1910: M. Weiss, "Sur un travail du Dr. Lombard, intitulé: contributions à la séméiologie de la surdité. Un nouveau signe pour en dévoiler la simulation," *Bull. Acad. Nat. Med. (Paris)* 44, 127-130 (1910). The account entered in the *Academy Bulletin* has been translated by R. F. Sullivan: "Report on Dr. Lombard's Original Research on the Voice Reflex Test for Malingering," *Acta Otolaryngol.* 56, 490-492 (1963). Lombard's own report²³ was published in the *Annales des Maladies de L'Oreille, du Larynx, du Nez et du Pharynx*, which he edited.

⁶ A. Moulouguet, *Manuel d'Expertise en Otologie* (Masson et Cie, Paris, 1933), pp. 14-16.

⁷ J. E. Fournier, "Le dépistage de la simulation auditive," *Exposés Ann. Oto-Rhino-Laryngol.* 107-126 (1956). [English transl.: *Transl. Beltone Inst.* 8, 1-23 (1958)].

⁸ "A subject raises his voice to above normal levels in the presence of an intense noise . . . Everything happens as if the subject were for the moment like a hard-of-hearing person." —B. T.

I. METHOD

A. Subjects

In the study by Lane, Catania, and Stevens,² separate groups of subjects were used to determine each of the underlying scales and the two validating functions. In this study, noise-compensation, sidetone-compensation, matching, sone, and autophonic functions were obtained in that order from each of 10 subjects. Paid male college students served in the five consecutive experiments, separated by 10-min breaks, in a single session lasting about 1½ h.

B. Procedure

For the noise-compensation and sidetone-compensation experiments, each pair of subjects provided a pilot and a navigator for "a communications experiment under simulated aircraft conditions." The pilot communicated code words, from a list described below, always in the context of the carrier phrase, "From here on, take _____ as your position." The navigator, listening over an interphone with his back to the pilot, wrote down each code word on a pad in plain view. If the transcription was correct, or if it was a homophone, the pilot said "Yes." The experimenter, located in the control room, disconnected the interphone while he adjusted the noise or sidetone level for the next trial, and then he illuminated the pilot's panel light, signaling him to proceed to the next word. If the transcription was incorrect, the pilot repeated the carrier and code word until a correct transmission was achieved, which always occurred within three attempts.

With the completion of these two experiments, the navigator retired to a ready room while the pilot served in the remaining three experiments. Then the navigator was recalled; he and the pilot exchanged roles and the five experiments were repeated.

In the noise-compensation experiment, four noise levels, 71, 75, 79, and 83 dB (SPL), were presented over the interphone in a descending and then ascending order of intensities that recycled six times. The first two cycles provided 16 practice trials, not included in later computations, while the last four cycles yielded eight determinations for each noise level. A "standard" level of sidetone gain was supplied by the interphone: 7 dB below the SPL detected by the microphone at 1 in. from the pilot's lips.³

In the sidetone-compensation experiment, four levels of sidetone gain, -4 , 0 , $+4$, and $+8$ dB (*re* "standard") were presented, 12 times each, in a quasirandom order; each level followed every level three times. A constant level of noise, 75 dB (SPL), was maintained in the interphone (except when it was disconnected between trials).

In the matching experiment, the criterion stimuli were six noise levels at 5-dB intervals from 65 to 90 dB (SPL). Each noise level appeared six times in a quasi-

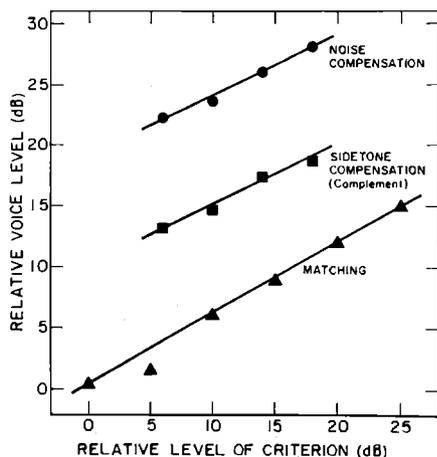


FIG. 1. Effect on voice level of (1) changes in the level of a sound that speakers were instructed to match, (2) changes in sidetone amplification during communication over an interphone, and (3) changes in noise level during communication over an interphone. Each point is the decibel mean of (1) 60 determinations, six from each of 10 subjects, (2) 96 determinations, 12 from each of eight subjects, and (3) 80 determinations, eight from each of 10 subjects. To facilitate comparison, the complement of the sidetone-compensation function is shown (not comprising two individual functions that were nonmonotonic). Absolute values (decibels SPL) may be recovered with these corrections to coordinate values: (1) $x+65$, $y+85$; (2) $104-x$, $y+80$; (3) $x+65$, $y+73$.

random order, such that each level followed every level once. The speaker matched the loudness of each criterion sound, after its 3-sec presentation, by uttering a word from the list provided.

The loudness-scaling experiment used the same series of criterion sounds as the matching experiment. The method of magnitude estimation was employed.⁹ For each criterion presented, beginning with the standard at 75 dB (SPL), the subject gave a numerical estimate of loudness which bore the same ratio to 10 as the loudness of the noise bore to the standard.

To measure the autophonic scale of voice level, the method of magnitude production was employed.² The speaker was given a list of words and asked to utter the first at medium level. To the magnitude of this response, the experimenter assigned the numerical value 10. A series of values (2.5, 5, 10, 20, 40) were then named in irregular order, and the speaker was asked to respond to each by uttering the following word on the list with a voice level of proportionate magnitude. Each of the values was presented 10 times in a quasirandom order such that each value followed every value twice.

C. Apparatus and Materials

The pilot and navigator were seated on opposite sides of a table, one meter from each other, in an audiometric room (IAC 1602-A-CT-R). They wore matched headsets (TDH-39 earphones; NAF 4890-1 and MX-41/AR cushions, respectively) connected in series. The

⁹ S. S. Stevens, "The Direct Estimation of Sensory Magnitudes—Loudness," *Amer. J. Psychol.* **69**, 1-25 (1956).

pilot's microphone (Electrovoice 6493), securely fastened to his headset at 1 in. from the lips, was connected to a tape recorder (Ampex 300). To measure voice levels to an accuracy of ± 0.5 dB, the recorder output was fed through an amplifier (Brüel & Kjær 2603, weighting curve B) to a strip-chart recorder (Brüel & Kjær 2305; rms response; 500 mm/sec writing speed). The tape recorder also supplied sidetone to the headsets through an attenuator (Hewlett-Packard 350 BR), mixer (Ampex MX-35), and amplifier (General Radio 1206-B). Finally, white noise was mixed with sidetone at various levels by connecting a noise generator (Grason-Stadler 901A) in series with an attenuator (General Radio TBR) and the mixer (with suitable impedance-matching transformers).

Voice, noise, and sidetone levels were determined with the aid of a Brüel & Kjær calibration system including a calibrated condenser microphone (type 4132) and the associated amplifier and strip-chart recorder. In order to calibrate the strip-chart recordings, the pilot's microphone and the condenser microphone were interchanged several times in front of a loudspeaker whose output was varied widely in intensity and frequency. To calibrate the four noise levels and the four sidetone levels, the earphones were suitably mounted on an artificial ear (Brüel & Kjær 4151) supplying the calibration system.

Each of the subjects in a pair used a different word list in each of the four experiments that required them. The 50 words in each of these phonemically-balanced, CNC lists were randomly ordered (Lehiste and Peterson¹⁰).

II. RESULTS

Figure 1 shows the effect on voice level of (1) changes in the level of a sound that speakers were instructed to match, (2) changes in sidetone amplification during communication over an interphone, and (3) changes in noise level during communication over an interphone. It is evident that these three operations have approximately the same effect, a change in voice level about half as great as the change in criterion level, consistent with the prediction from the underlying sensory scales. The slopes of the straight lines are, respectively, 0.59, 0.50, and 0.50.

Figure 2 shows the results of measuring the sone and autophonic functions of the same group of subjects whose matching and compensation functions appear in Fig. 1. The slopes of the straight lines are 0.62 and 1.19, respectively, and their ratio is 0.52. This outcome is consistent with previous findings^{2,11,12} and with the

¹⁰ I. Lehiste and G. E. Peterson, "Linguistic Considerations in the Study of Speech Intelligibility," *J. Acoust. Soc. Amer.* **31**, 280-286 (1958).

¹¹ H. L. Lane, "Psychophysical Parameters of Vowel Perception," *Psychol. Monogr.* **76**, No. 44, 1-25 (1962).

¹² H. L. Lane, "The Autophonic Scale of Voice Level for Congenitally Deaf Subjects," *J. Exptl. Psychol.* **66**, 328-331 (1963).

slopes of the three cross-modality functions shown in Fig. 1.

III. DISCUSSION

The results show that when speakers vary autophonic level in order to match changes in the loudness of a criterion, or in order to compensate for changes in the apparent loudness of their voices, or in order to compensate for changes in the loudness of ambient noise—in all these tasks requiring cross-modal integration, about the same 1:2 relation is found between the dynamics of listening and speaking. This generalization is borne out by numerous studies that have reported equal-sensation functions, sidetone-penalty functions, or communication-in-noise functions. Carried out under a wide variety of conditions, some of these studies confirm the congruence of the three kinds of functions and the 1:2 disparity in sensory dynamics that the functions reflect. Others clarify the effects of certain parametric conditions; specifically, monaural vs binaural presentation, the premium on intelligibility when speaking, and the range of changes in the criterion.

A. Matching

Figure 3 shows the equal-sensation functions obtained in several studies when speakers matched their autophonic levels to changes in the loudness of criterion sounds. Black¹³ asked each of 24 speakers to utter the word *top* at the same loudness as that of a noise (filled triangles) or a sweep-frequency tone (inverted triangles) whose level varied over 30 dB in 6-dB steps. Voice levels, averaged over two presentations of ascending, descending, and random series of criterion levels, are fit by straight lines (method of least squares) with slopes of 0.73 and 0.67, respectively.

Lane, Catania, and Stevens² employed 10 subjects, the vocal response [a], and a noise that ranged over 50 dB in 10-dB steps, presented in irregular order. The matching function had a slope of 0.51 in one experiment, using a loudspeaker to present stimuli (open circles), and 0.52 in another, using earphones (open triangles). Lane¹¹ had each of nine speakers imitate the disyllable [ba-ba], with iambic or trochaic stress, 42 times. The ratio of syllable intensities varied from -15 dB to +15 dB in 5-dB steps. The nonsense word was prerecorded six times at each of the seven stress levels, then presented over a loudspeaker in an anechoic chamber. In Fig. 3 (filled circles), the stress-matching function has a slope of 0.54.

Irwin and Mills¹⁴ performed the converse of a matching experiment by measuring "pairs of sensations corresponding to equal stimuli . . . instead of measuring

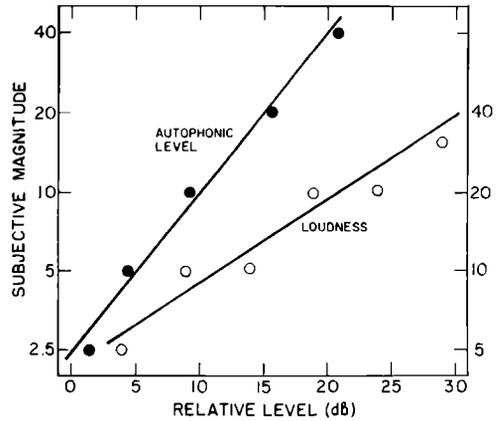


FIG. 2. Sone function and autophonic function of the same group of subjects whose matching and compensation functions appear in Fig. 1. Each point on the sone function (open circles, right-hand ordinate) is the median of 54 determinations, six from each of nine subjects. Each point on the autophonic function (filled circles, left-hand ordinate) is the mean of 100 determinations, 10 from each of 10 subjects. Absolute levels (decibels SPL) may be recovered by adding to the abscissa values of 61 dB for the sone function, and 81 dB for the autophonic function.

pairs of stimuli corresponding to equal sensations" (p.144). An instructor produced six different autophonic levels of the vowel [a] while 25 students estimated the loudness of the corresponding voice levels. The order of levels was irregular, each level appeared twice, and the entire experiment was replicated with a second class of 19 students. The predicted slope of the function relating autophonic levels to loudness estimates was 0.50; the obtained slopes were 0.53 and 0.52. Although the results are in subjective rather than physical units, the former function is shown in Fig. 3 (squares), converted to decibels, for comparison.

B. Sidetone Compensation

Figure 4 shows the sidetone-compensation functions obtained in several studies when speakers adjusted their autophonic levels to compensate for changes in their sidetone loudness, with or without instructions to do so.

Lane, Catania, and Stevens² instructed each of 10 speakers to hold the loudness of his voice constant, as he perceived it, during production of the vowel [a]. Concurrent changes in sidetone ranged in 10-dB steps from 20 dB below to 40 dB above standard sidetone. The sidetone-compensation function had a slope of -0.46 (open squares). When sidetone was varied only monaurally, however, the compensation function was, not surprisingly, flatter: -0.40 (open circles). Under this condition, which prevails in studies of telephonic sidetone penalty, the sidetone is constant, not eliminated, in one ear, while it is changing in the other; therefore, the net change may be less. Furthermore, the

¹³ J. W. Black, "Control of the Sound Pressure Level of Voice," Joint Project Rep. No. 42, Bur. Med. Surgery, U. S. Navy Project No. NM 001 104 500.42 (1955).

¹⁴ R. J. Irwin and A. W. Mills, "Matching Loudness and Vocal Level: An Experiment Requiring no Apparatus," *Brit. J. Psychol.* **56**, 143-146 (1965).

¹⁵ G. S. Reynolds and S. S. Stevens, "Binaural Summation of Loudness," *J. Acoust. Soc. Amer.* **32**, 1337-1344 (1960).

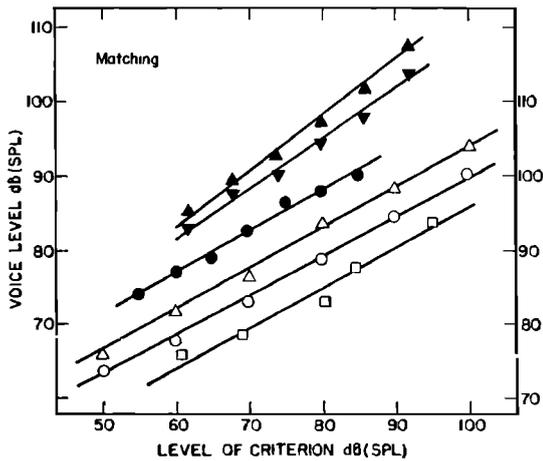


FIG. 3. Equal-sensation functions obtained in several studies when speakers matched their autophonic levels to changes in the loudness of criterion sounds. To compare measurements obtained under different conditions, a criterion-level correction x and a voice-level correction y were added to each set of data before plotting in Figs. 3-5. This leaves the functions unchanged in slope but aligns them with respect to a common set of reference conditions, viz., 82 dB (SPL) at 1 in. from the lips¹⁷ for voice level, and, consequently, 75 dB (SPL) at the entrance to the meatus³ for criterion level. x, y corrections are given in decibels for each function, along with an asterisk if only relative levels are reported in the original study. Open data points refer to the right-hand axis, filled to the left. These criterion sounds have been used: white noise (filled triangles, 0, 15.5) and sweep-frequency tones (inverted triangles, 0, 15.5); disyllables with varying stress (filled circles, 70*, 82*); white noise presented by loudspeaker (open circles, 50*, 41*) and by earphones (open triangles, 50*, 50*). The converse of a matching experiment gave the last function (squares), obtained by measuring pairs of sensations corresponding to equal stimuli instead of pairs of stimuli corresponding to equal sensations. Although the results are in subjective rather than physical units, they are shown, converted to decibels for comparison (55*, 62*).

monaural loudness scale is a little flatter than the sone scale: 0.54 vs 0.60 (Ref.15).

Fletcher, Raff, and Parmley¹⁶ instructed 60 speakers to read monosyllables at a conversational level into a telephone microphone under monaural sidetone amplifications ranging from 0 to 30 dB in 10-dB steps (filled inverted triangles). Under similar conditions, Noll^{17,18} had telephone talkers read prepared passages (hexagons). The sidetone-penalty functions were found to have slopes of -0.25 and -0.30 , respectively. These results probably reflect an attenuation of the effect of sidetone change on voice level due not only to exclusively monaural alterations in sidetone but also to the absence of any communication task. The importance of a premium on intelligibility receives more evidence and a rationale in the next section.

¹⁶ H. Fletcher, G. M. Raff, and F. Parmley, "Study of the Effects of Different Amounts of Sidetone in the Telephone Set," Western Electric Co., Rep. No. 19412, Case No. 120622 (1918).

¹⁷ A. M. Noll, "Effects of Head and Air-Leakage Sidetone during Monaural-Telephone Speaking," J. Acoust. Soc. Amer. 36, 598-599 (L) (1964).

¹⁸ A. M. Noll, "Subjective Effects of Sidetone during Telephone Conversation," IEEE Trans. Comm. Electron. 83, 228-231 (1964).

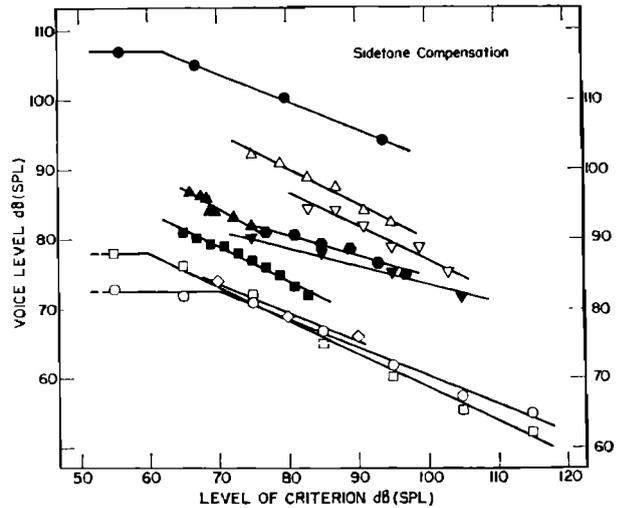


FIG. 4. Sidetone-compensation functions obtained in 10 experiments when speakers adjusted their autophonic levels to compensate for changes in their sidetone loudness, with or without instructions to do so. (Open data points refer to the right-hand axis, filled to the left.) *Binaural sidetone compensation*: Under instructions to hold sidetone loudness constant while vocalizing [a] (open squares, 75*, 13*); when vocalizing [a] at "medium level" (diamonds, 75*, 40*); reading sentences during flight testing of aircraft interphones at 5000 ft (open triangles, 67*, 168-x*), 35 000 ft (open inverted triangles, 67*, 168-x*), and on the ground (filled circles, 94*, 51*); reading phrases after noise-induced temporary hearing loss (filled triangles, 75*, 82*). *Telephonic-sidetone penalty*: Under instructions to hold sidetone loudness constant while vocalizing [a] (open circles, 75*, 35*); during business telephone calls (filled squares, 75*, 82*); reading passages into a telephone (hexagons, 89*, 82*); reading monosyllables into a telephone (filled inverted triangles, 75*, 50*, re: Lane, Catania and Stevens²).

Incidentally, Noll worked out a procedure to correct the artifactual levelling off of the sidetone-penalty function at very low levels of receiver gain. When the total sidetone change (receiver, head, and air-leakage sidetone) is taken into account, the sidetone-penalty function is linear throughout (in decibel coordinates).

McKown and Emling¹⁹ monitored business calls made by telephone company employees using special facilities that permitted monaural changes in sidetone. They found that increases in telephone sidetone at the transmitter produced decreases approximately half as great (in decibels) in the "effective volume" at the receiver (filled squares; slope -0.49). For example, when the speaker's sidetone was increased 10 dB, his listeners would ask him to repeat what was said about as often as when the volume in their receivers was decreased 5 dB. It is not surprising that a 10-dB increase in the speaker's sidetone had the same effect as a 5-dB decrease in the listener's volume, since a 10-dB increase in sidetone in fact produces a 5-dB decrease in volume, according to the function predicted from the disparity of sone and autophonic scales.

¹⁹ F. W. McKown and J. W. A. Emling, "System of Effective Transmission Data for Rating Telephone Circuits," Bell System Tech. J. 12, 331-346 (1933).

Licklider and Kryter²⁰ had nine speakers read sentences during flight testing of aircraft interphones with various voltage gains. Signal levels produced at the interphone headset were measured during the articulation tests. The headset voltages have two components, one of which is due to the gain setting of the interphone and one to the vocal level produced. The vocal levels were obtained by subtracting the changes in voltage gain introduced by the experimenter from the changes in voltage measured at the headset. The sidetone-compensation function had a slope of -0.50 for flights at 5000 ft (open triangles), and -0.46 for flights at 35 000 ft (open inverted triangles).

In a comparable laboratory experiment, Lightfoot and Morrill²¹ employed 16 naval officers who read a different intelligibility test (24 words) at each of four levels of sidetone intensity. "The reader wore a service headset with conventional dynamic headphones and doughnut ear cushions. A constant level of in-circuit noise was in the headphones all the time, comparable to that induced by an open microphone in an airplane . . . The order of sidetone conditions was rotated from speaker to speaker" (p. 1). The obtained slope was -0.41 (filled circles).

In the course of measuring the effect of augmented sidetone on the slope of the autophonic scale (the effect is quite minor), Lane, Catania, and Stevens² observed that the speaker's "modulus" for magnitude productions—that is, the voice level he considers medium—varied systematically with sidetone gain. The measured slope was -0.41 (diamonds).

Finally, Black²² measured the effect of sidetone reduction on speaking level by inducing temporary threshold shifts. He subjected 144 male college students to 2 h of noise at 110 dB (SPL) and then measured, at 3 min intervals after the termination of the noise, both hearing loss and the increase in vocal level during the reading of phrases. He found that "the effect [of noise] upon hearing is greater than the compensating effect upon speaking" (p. 77). The sidetone compensation function has a slope of -0.57 (filled triangles).

C. Noise Compensation

Lombard²³ may have been the first to propose a relation between the increase in speaking level caused by hearing loss and that caused by increased noise. The present experiment confirmed the relation as shown by the juxtaposition of sidetone-penalty and Lombard-

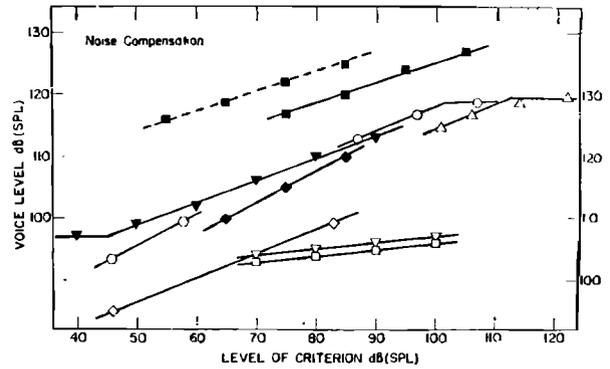


FIG. 5. Noise-compensation functions obtained in 10 experiments when speakers adjusted autophonic levels to compensate for changes in noise levels during communication or reading aloud. (Open data points refer to the right-hand axis, filled to the left.) These tasks have been used: communicating words, reproduced by listeners (filled diamonds, 0,0); reading word lists or sentence lists into a tape recorder (open squares and inverted triangles, respectively, 0,32); conversing with the experimenter (filled inverted triangles, 0,97*); conversations by pairs of communicators (open diamonds, 0,95*); communicating sentences, reproduced by listeners, over a two-way loudspeaker communication system (hexagons, 0,32); shouting sentences to listeners in high ambient noise (circles, 0,32); reading word lists to listeners while wearing earplugs (filled squares, broken line, $-20,38$) and with plugs removed (solid line, 0,38); shouting sentences (triangles, 0,123*).

reflex functions in Fig. 1. It is similarly confirmed by comparing the results of Black's measurements of voice level, made under conditions of temporary hearing loss (Fig. 4), with those of Webster and Klumpp²⁴ made under varying noise conditions (Fig. 5, filled diamonds). These investigators had three pairs of subjects communicating 50 words (from phonetically balanced lists) in the presence of ambient-noise levels of 65, 75, and 85 dB (SPL), presented in ascending and descending series. There was a premium on intelligibility, since the listener was required to repeat each word and the speaker was required to repeat the transmission if the listener's repetition was not correct (up to a maximum of three repetitions). The Lombard reflex function, based on average voice levels of six subjects (speakers and listeners pooled), has a slope of 0.50. In other words, speakers compensate only halfway (in decibel units) for increases in the ambient noise during communication, just as they compensate only halfway for decreases in their signal level.

The results of seven other studies of voice level in noise are shown in Fig. 5; it is helpful to consider these studies in an order dictated roughly by the weighting that their methods give to intelligible communication. At the one extreme, there can be a requirement of correct transmission during face-to-face conversation. Webster and Klumpp's method (and that of the present study) are near this end of the continuum. At the other extreme, a speaker can be asked to read a list of words

²⁰ J. C. R. Licklider and K. C. Kryter, "Articulation Tests of Standard and Modified Interphones Conducted during Flight at 5000 and 35 000 ft," OSRD Rep. 1976, PB 5505 (1944).

²¹ C. Lightfoot and S. N. Morrill, "Loudness of Speaking: the Effect of the Intensity of Side-Tone upon the Intensity of the Speaker," Joint Project Rep. No. 4, Bur. Med. Surgery, U. S. Navy Project No. 001.053 (1949).

²² J. W. Black, "The Effect of Noise-Induced Temporary Deafness upon Vocal Intensity," Speech Monogr. 18, 74-77 (1951).

²³ E. Lombard, "Le signe de l'élévation de la voix," Ann. Maladies Oreille, Larynx, Nez, Pharynx 37, 101-119 (1911).

²⁴ J. C. Webster and R. G. Klumpp, "Effects of Ambient Noise and Nearby Talkers on a Face-to-Face Communication Task," J. Acoust. Soc. Amer. 34, 936-941 (1962).

into a tape recorder. This is the method employed by Dreher and O'Neill²⁵ and, as you might expect, their 15 speakers did not attempt to raise their voices very much when the noise in their earphones increased: the noise-compensation slopes were 0.10 for sentences (open inverted triangles) and 0.11 for words (open squares).

In between the two extremes are varying degrees of emphasis on intelligibility provided by a variety of methods. Korn²⁶ engaged his 50 speakers in conversation (and also had them read sentences) but there was no requirement for correct transmission. Noise levels ranged, in ascending and descending series, from 40 to 90 dB in 10-dB steps. The noise-compensation function had a slope of 0.38 (filled inverted triangles). A comparable slope, 0.39, is yielded by Gardner's²⁷ measurements of voice level under two of five noise levels presented during face-to-face conversations by eight pairs of subjects (open diamonds). When speakers read groups of five sentences, which listeners had to reproduce correctly, a flatter function, slope 0.35, was obtained. Using a like task and number of communicators, Gardner²⁸ substituted a two-way loudspeaker communication system for the normal airpath of face-to-face communication. He varied the ambient noise over a range of 37 dB and the orthotelephonic gain from +10 to -40 dB. The over-all slope of the noise-compensation function, obtained when speakers read sentences that listeners had to reproduce correctly, varied from 0.29 to 0.61 (extrapolated), depending on the reduction in system gain. Steeper slopes were obtained as the deteriorating signal-to-noise ratios increasingly required the talkers to speak up in order to maintain intelligibility. With an orthotelephonic gain of -35 dB, voice level rose 6 dB under a 12-dB increase in ambient noise (hexagons).

Gardner's measurements also shed light on the influence of another parametric variable, the range of criterion levels employed. On the one hand, as the ambient-noise level is reduced, the voice level cannot continue to fall indefinitely at the rate dictated by the noise-compensation function. The functions obtained by Gardner²⁸ and Korn²⁶ indicate that the voice level approaches a minimum as very low ambient-noise levels are approached. On the other hand, the complementary "ceiling effect" may be expected at very high noise levels. Pickett²⁹ conducted sentence intelligibility tests with intense white noise at the talkers' position (87,

97, or 107 dB SPL). His eight subjects, who were told that they must shout to be heard by listeners 8 ft away, raised their voices 4 dB, on the average, for the first 10-dB increment in noise, but only 1 dB for the next 10-dB increment in noise (open circles).

Pickett's study was actually an extension of an earlier experiment by Kryter³⁰ who had eight speakers read phonetically balanced word lists to listeners seven feet away in the presence of one of four noise levels between 75 and 105 dB (SPL). The noise-compensation function had a somewhat flatter slope, 0.33, under these conditions of reading without correction (filled squares). When Kryter's speakers wore earplugs, bone-conducted sidetone was probably increased,³ while air sidetone and the ambient noise were attenuated; the net effect was a drop in voice level from 1 to 2 dB and no change in slope (broken line).

The remaining noise-compensation function in Fig. 5 (open triangles) was obtained with even higher noise levels than those used by Pickett. The ceiling effect is clearly shown. Hanley and Steer³¹ instructed their 48 speakers to read a passage "as though communicating the information to a listener." With the first 5 dB increase in earphone noise (from 101 to 106.2 dB SPL), the speakers raised their vocal levels approximately half as many decibels (slope 0.45). With each successive 8-dB increase in noise, there was a smaller compensatory increase in vocal level, "as the subjects' limits of response potentialities are approached" (p. 368).

D. Summary

The results of the present investigation, together with those of prior studies, lead to the following summary statement and hypothesis concerning the effects on communication of the disparity between the sone and autophonic scales. During communication, the speaker undertakes, at most, to compensate fully for changes in the signal-to-noise ratio; he matches apparent changes in signal level inversely and changes in noise level directly. A perfect match is achieved subjectively when there is a 1:2 mismatch in physical units, as a result of the disparity between sone and autophonic scales. Therefore, the compensation is at best only halfway effective (in decibels).

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³⁰ K. D. Kryter, "Effects of Ear Protective Devices on the Intelligibility of Speech in Noise," *J. Acoust. Soc. Amer.* **18**, 413-417 (1946).

³¹ T. D. Hanley and M. Steer, "Effect of Level of Distracting Noise upon Speaking Rate, Duration and Intensity," *J. Speech Hearing Disorders* **14**, 363-368 (1949).

²⁵ J. J. Dreher and J. J. O'Neill, "Effects of Ambient Noise on Speaker Intelligibility of Words and Phrases," *Laryngoscope* **68**, 539-548 (1958).

²⁶ T. S. Korn, "Effect of Psychological Feedback on Conversational Noise Reduction in Rooms," *J. Acoust. Soc. Amer.* **26**, 793-794 (1954).

²⁷ M. B. Gardner, "Effect of Noise on Listening Levels in Conference Telephone," *J. Acoust. Soc. Amer.* **36**, 2354-2362 (1964).

²⁸ M. B. Gardner, "Effect of Noise, System Gain, and Assigned Task on Talking Levels in Loudspeaker Communication," *J. Acoust. Soc. Amer.* **40**, 955-965 (1966).

²⁹ J. M. Pickett, "Limits of Direct Speech Communication in Noise," *J. Acoust. Soc. Amer.* **30**, 278-287 (1958).