THE LOMBARD SIGN AND THE ROLE OF HEARING IN SPEECH

HARLAN LANE *and* BERNARD TRANEL

University of Michigan, Ann Arbor, Michigan

Lombard noted in 1911 that a speaker changes his voice level similarly when the ambient noise level increases, on the one hand, and when the level at which he hears his own voice (his sidetone) decreases, on the other. We can now state the form of these two functions, show that they are related to each other and to the equal-sensation function for imitating speech or noise loudness, and account for their form in terms of the underlying sensory scales and the hypothesis that the speaker tries to maintain a speech-to-noise ratio favorable for communication.

Perturbations in the timing and spectrum of sidetone also lead the speaker to compensate for the apparent deterioration in his intelligibility. Such compensations reflect direct and indirect audience control of speech, rather than its autoregulation by sidetone. When not harassed by prying experimenters or an unfavorable acoustic environment, the speaker need no more listen to himself while speaking than he need speak to himself while listening.

In the course of a distinguished career as France's first *Oto-rhino-laryngologiste des Hôpitaux*, Etienne Lombard published 44 articles, among them the classic "*Le signe de l'élévation de la voix*" (1911).[1] Lombard made the important discovery described in this article during the summer of 1909 at the *Hôpital Lariboisière*.

A year before, R. Bárány, at the University of Vienna, had patented and reported a device that delivered an intense noise to one ear, thus permitting examination of the other ear under completely monaural conditions. Using this device, among others,[2] Lombard presented the noise to a patient engaged in conversation. What he observed has come to be known as the Lombard reflex. When the noise began, the patient increased his vocal level; when it stopped, he lowered his voice to its former level. Neither change seemed to be conscious.

In a brilliant series of parametric studies, Lombard elaborated the basic discovery, reporting his findings first to the Academy of Sciences in August

[1] Etienne Lombard (1868-1920). For obituaries, see Lermoyez (1920), Aucoc (1920), and *Ann. Mal. Oreil.* (1922). For biographical data see Fischer (1932, p. 938) and Bloch (1949).

[2] Halphen (1910a) and Gibert (1911) describe the devices available at the time for excluding hearing in one ear—aerodynamic, mechanical, and electrical. Bárány's device was mechanical (Bárány, 1908); a clockwork hammer struck a membrane, and the noise produced was conducted to the ear by an aural speculum. Lombard's was electrical (Lombard, 1911); an electromagnetic vibrator supplied telephone receivers.

of 1909, then to the Academy of Medicine in April of the following year.[3] During the same month, his student E. Halphen presented a dissertation that included a discussion of the "*signe de Lombard*" (Halphen, 1910a,b), and in October, W. Weiss read a report of Lombard's work into the proceedings of the Academy of Medicine (Weiss, 1910; Sullivan, 1963). The preceding chronology of events was the subject of considerable attention when Lombard found in 1910 that his discovery was reported in German publications but attributed there to Bárány. This led to a series of acerbic exchanges in print between the two investigators (Lombard, 1910a; Bárány, 1910; Lombard, 1910b); the matter of priority was finally laid to rest when Donald Schearer, the English physician who had first carried the word from Paris to Vienna in November of 1909, came forward with his account (Sebileau, 1911).

Lombard's discovery and his subsequent findings are important because of their contribution to fully four areas of scientific inquiry: (1) the development of tests of hearing loss and especially of simulated hearing loss, (2) the analysis of speech communication in noise, (3) the study of the general dynamic relations between hearing and speaking, embracing such related phenomena as imitation and speaking under conditions of altered auditory feedback, and finally (4) the theory of the speech mechanism as a servomechanism. These are intimately related problems, as Lombard was aware, and he saw implications of his work for each of the four areas. Not so with later scientists, however. Many have failed to appreciate the relevance of knowledge accumulated in each of these areas for the others; most have wrongly relegated Lombard's work exclusively to the domain of hearing tests; some have misinterpreted the implications of his findings, particularly as regards autoregulation by the speech mechanism. With the hindsight of six decades of research, it seems time to review the Lombard sign in all of its ramifications, and to synthesize a general statement of the regulation of speech by hearing, insofar as this is now possible.

DETECTION OF HEARING LOSS AND ITS SIMULATION

The use of the Lombard sign in medicolegal evaluations of hearing, for which it continues to be widely employed, follows from Lombard's first experimental elaboration of his basic finding. Using a subject with normal hearing, Lombard presented an intense noise first to one ear, then to the other, finally to both simultaneously. With monaural noise, the speaker raised his voice somewhat; with binaural noise, however, he raised his voice much more, nearly shouting: Next, using a patient with unilateral deafness, Lombard presented the noise first to the impaired ear, then to the normal ear. In the first case, the patient raised his voice slightly or not at all; with his "good ear" subjected to the noise, however, he proceeded to shout, much as his normal counterpart did under binaural noise.

[3]Letter to the Academy of Sciences, No. 7527, August 30, 1909. Also see: Académie de Médecine (1910).

From this observation follows the test that Lombard's *rapporteur*, Weiss, called simple, reliable, and objective. If one ear is normal or only moderately impaired, and noise is introduced into this ear without evoking the Lombard sign, then the subject is not deaf in the other ear; if the sign is evoked, then there is total or extensive hearing loss in that ear. Thus it is possible to expose someone who is feigning monaural deafness, either consciously—in order to avoid military service or to enhance compensation benefits, for example—or unconsciously, as in some cases of hysteria (Harbert, 1943). The malingerer claiming deafness in one ear will continue to read or speak with only a slight increase in voice level, no matter which ear receives the noise. It is more difficult and hence unusual to feign binaural deafness, but this, too, may be exposed by the Lombard test, merely applying the noise binaurally; a positive sign unmasks the malingerer (Grant, 1911; Mackenzie, 1929; Weber, 1931; Russel, 1934; Maffeo, 1934. Application of the Lombard test is discussed in articles by Egan, 1971; Appaix and Olivier, 1970; Chailkin and Ventry, 1963; Azzi, 1962; Newby, 1958; Fournier, 1956; Portmann and Portmann, 1953; and in the doctoral dissertations of Thomas, 1961; Dupon, 1952; Montagne, 1951; and Gosset, 1942.)

Five characteristics of the Lombard sign, some of them also constraints on its use in testing, should be mentioned here. First, the sign is not a perfectly reliable index of hearing loss. For example, with binaural exposure to intense noise, some normal subjects do not evince the sign, while some hard-of-hearing subjects do (Panconcelli-Calzia, 1955). More crucial for the Lombard test, some subjects can simulate the sign; the point has been disputed, but most investigators agree that some malingerers can, with a great deal of advance coaching, elude detection (Kerrison, 1918; Pitman, 1943; Priest, 1945; Taylor, 1949; Waldron, 1960). Incidentally, the Lombard test has also been used as a check on organic involvement in certain voice disorders; if the vocal symptoms disappear during the noise, then some psychopathology is implicated, according to Tarneaud (1941); Lombard and Baldenweck (1916) detected and treated a case of hysterical mutism in this way.

The acoustic correlates of the Lombard sign, the second characteristic to be noted, make its simulation more difficult. Berger (1932) found that when subjects tried to simulate the Lombard sign they underestimated the intensity changes and grossly overestimated the pitch changes. The change in pitch during the Lombard sign, also noted by Lombard (1911), Pitman (1943), and Dicello (1943), and studied by Tarneaud (1941), is the normal accompaniment of a change in voice level, predictable from the mechanics of glottal excitation in speech (Fant, 1960; Lane, 1962). When speakers hold their voice levels constant despite the introduction of ambient noise, their mean fundamental frequency is also constant (Gremy, Chevrie-Muller, and Rousseau-Grenet, 1966). Perhaps the changes in pitch are greater when simulating the sign because a second mechanism for increasing voice fundamental frequency is brought into play—an increase in vocal cord tension. Berger reported that the pitch changes accompanying the Lombard sign are, in any event, highly variable and insensitive compared to the intensity changes. In addition, the "fine control" of pitch may be poorer during the Lombard sign (Mattsuzaki and Iwamura, 1965; Gremy, Chevrie-Muller, and Rousseau-Grenet, 1966; Elliott and Niemoeller, 1970).

The rate of speaking is uncorrelated with the Lombard sign, according to several investigators (Berger, 1932; Waldron, 1960; Charlip and Burk, 1969), but Rubenovitch and Pastier (1938) found some characteristic increase in rate. As for the effects of noise on the duration of speech segments, reliable increases were found by Fónagy and Hermann (1964), Ladefoged (1967), Charlip and Burk (1969), and Fricke (1970), but not by Berger (1932). Pitman (1943) also reported a "blurring in articulation," and Pickett (1956, 1958) found that increases in high noise levels yielded less intelligible speech (for constant signal-to-noise ratio).

The degree of hearing loss is a third factor that influences the outcome of the test. In follow-up experiments with patients suffering from various degrees of monaural and binaural hearing loss, Lombard found that the worse the hearing in the experimentally deafened ear, the more noise is required to evoke the increase in voice level. Tato (1954) and Takakura (1957) find here the basis for an "objective audiometry." Lombard also observed, consistently, that the worse the hearing in the other ear, the less noise is required to obtain a given increase in voice level. On the one hand, this may be the first evidence we have that the speaker's increase in voice level is controlled not only by his perception of the noise, but also by his perception of his own voice. On the other hand, this interpretation conflicts with Taylor's finding (1949) that a speaker deaf in one ear raised his voice under masking of the other ear as much as normal subjects did.

Fourth, the nature of the hearing loss is a parameter of the Lombard sign. As Lombard pointed out, the test is primarily suited to cases of perceptive deafness, where the lesion is located somewhere in the neural mechanism. This is because a speaker with conductive deafness, where there is interference with transmission of sound through the outer and middle ear, continues to hear his own voice with the defective ear, by virtue of bone conduction through the skull to the intact inner ear (Hood, 1962). Consequently, noise presented to the healthy ear does not evoke the sign. Lombard states that an obvious audiometric hearing loss in such cases indicates that disorders of the middle ear predominate over those of the inner ear, if any. Binaural noise will evoke the sign, in cases of conductive hearing loss, according to Moulonguet (1933), but this did not happen in the case reported by Lombard. Escat and Rigaud (1933) state that such patients may react to noise by speaking more softly, just as they react to excessive feedback of their own voice. In any case, most investigators agree that patients with conductive hearing loss speak too softly; 80% of them did in a large sample studied by Penn (1955). The explanation may be that the speaker overestimates his own voice level, or that he underestimates the ambient noise level which he normally uses as a guide to correct intensity. Perhaps he does both.

We have described briefly the probabilistic nature of the Lombard sign, its several acoustic concomitants, and the influence exerted by the nature and degree of concurrent hearing loss. The following section describes the fifth characteristic of the sign in detail—its variable magnitude controlled particularly by the level of the noise.[4] Since the sign is not an all-or-none response with a certain threshold and relatively fixed magnitude, the name "Lombard reflex" has misled some authors (for example, Newby, 1958). In fact, noise level and voice level grow together. In Lombard's own words, there is "un véritable parallélisme entre le degré de l'assourdissement et celui de l'élévation de la voix, celle-ci montant progressivement jusqu'à atteindre l'intensité de la voix criée" (1911, p. 108).

THE LOMBARD FUNCTION AND THE ANALYSIS OF SPEECH COMMUNICATION IN NOISE

Lombard stated that "plus le bruit de l'assourdisseur est intense, plus grande est l'élévation de l'intensité de la voix" (1911, p. 107). Later investigators were to state this relation quantitatively, although most were concerned with the effects of aircraft or other ambient noise on speech transmission. They were unaware that they were charting the Lombard function. Figure 1 shows the results from eight studies of the relation between

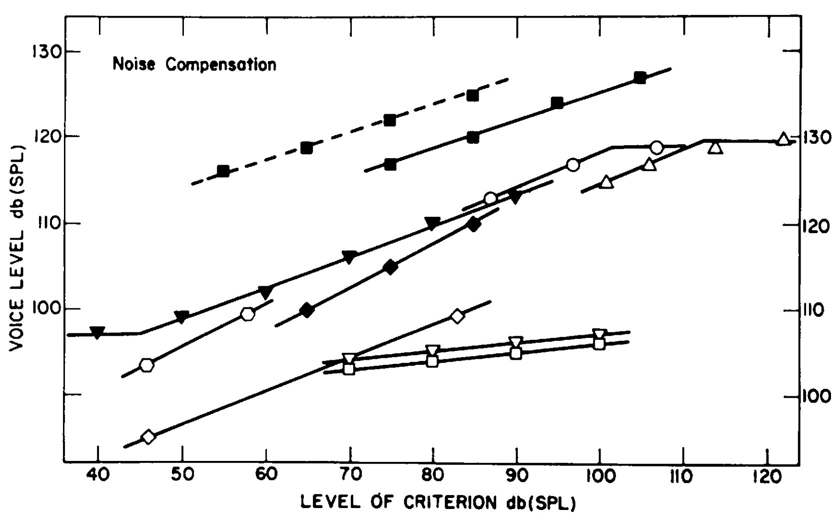

FIGURE 1. Noise-compensation functions obtained in 10 experiments when speakers adjusted autophonic levels to compensate for changes in noise levels during communication or reading aloud. See Table 1. (From Lane, Tranel, and Sisson, 1970. Open data points refer to the right-hand axis, filled to the left.)

[4]Hanley and Harvey (1965) built a device to judge the level of the sign reliably. Ruppman and Tegtmeier (1961) proposed measuring voice levels by determining the level of a just-masking noise. For further discussion of the measurement of vocal level, see Lane and Shinkman (1963).

noise level and voice level, studies carried out under widely different conditions. It is at once apparent that the Lombard function is reasonably well described by a straight line in decibel coordinates, with a slope in the region of one-half (making allowance for the upper limit on shouting, near 130 dB). This means that the speaker compensates about halfway (in decibel units) for each increase in noise; for example, a fourfold increase in noise is matched by a twofold increase in voice level.

The most obvious departure from this relation is found in the results of Dreher and O'Neill (1958), shown at the bottom of Figure 1. These investigators had speakers read prepared texts into a microphone while exposed to binaural earphone noise at various levels. The very flat noise-compensation functions they obtained are representative of those from several comparable experiments. Other studies with similar methods and results (reading task and flat noise-compensation functions) are Taylor (1949), Waldron (1960), Alpert (1965), Egan (1967), and Charlip and Burk (1969, word repetition). Tato (1954) obtained comparable slopes (0.10 to 0.20) with normal as well as hearing-impaired subjects; however, it is not clear which of several tasks mentioned, including reading, was employed. Black (1950c) and Atkinson (1952) used a reading task and pure-tone stimuli and obtained expectedly flat compensation functions. Yannoulis (1963) reported an average increase of 20 dB in voice level with the presentation of 90 dB of noise, and Takakura (1957), one of 9 dB with 70 dB noise, but the initial ambient noise levels are not reported in these studies.

These results reflect a sixth characteristic of the Lombard sign to be added to the preceding five; the magnitude of the response is governed by the premium on intelligible communication. As far back as 1910, Halphen noted that "le son de la voix de conversation se modifie encore mieux que le son de la voix de lecture" (p. 107), and the same conclusion has since been reached by Berger (1932), Tato (1954), and Egan (1967). At the one extreme, there can be no premium at all on intelligibility. Speakers merely asked to read a list into a microphone, for example, pay little heed to changes in the noise around them. At the other extreme, a high premium on intelligible communication presumably provides for low-redundancy conversation under marginal speech-to-noise ratios, with correct transmission required under nonsystematic changes in noise level. For example, Webster and Klump (1962) had pairs of subjects communicating under various levels of ambient noise, with the requirement that the listener repeat each word received, and that the speaker repeat the transmission if the listener's repetition was not correct. Under these conditions, the Lombard function had a slope of 0.5 (Figure 1).

In between the two extremes are varying degrees of emphasis on intelligible communication provided by a variety of methods (see Table 1). Korn (1954) engaged his 50 speakers in conversation and also had them read sentences, but there was no requirement for correct transmission, while noise levels varied in ascending and descending series. The noise-compensation function had a slope of 0.38. Gardner's (1964) measurements of voice level under two

TABLE 1. The slopes of noise-compensation functions obtained in experiments with diverse conditions and tasks, Figure 1.

Experimenters	*Conditions and Tasks*	*Figure*	*Symbols*
Webster & Klump (1962)	Communicating words reproduced by listeners	0.50	◆
Dreher & O'Neill (1958)	Tape recording words and sentences	0.11	▽ □
Korn (1954)	Conversing with the experimenter	0.38	▼
Gardner (1964)	Conversing with a listener	0.39	◇
Gardner (1966)	Reading sentences, reproduced by listeners, over an interphone; variable system gain	0.3-0.6	⬡
Pickett (1958)	Shouting sentences under high noise levels	0.40	○
Kryter (1946)	Reading word lists		
	With earplugs	0.33	■
	Without earplugs	0.33	■
Hanley & Steer (1949)	Shouting sentences under high noise levels	0.45	△

of five noise levels during face-to-face conversations gave about the same slope. In a later experiment, Gardner (1966) substituted a two-way loudspeaker communication system for the standard airpath between speaker and listener, enabling him to vary the transmission gain, relative to that standard, from +10 to −40 dB. When speakers read sentences over this system that listeners had to reproduce correctly, with ambient noise varying over 40 dB, the overall slope of the noise-compensation function ranged from 0.29 to 0.61 (extrapolated), depending on the transmission gain. Steeper slopes were obtained as the deteriorating signal-to-noise ratios increasingly required the talkers to speak up in order to maintain intelligibility. This study shows systematically the parametric control of the slope of the Lombard function by the premium on intelligibility.

Gardner's measurements also shed light on a seventh parameter of the Lombard sign, 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 Gardner (1966) and Korn (1954) 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. During sentence intelligibility tests with intense noise, Pickett's (1958) eight speakers raised their voices 4 dB, on the average, for the first 10-dB increment in noise, but only 2 dB for the next 10-dB increment in noise. When a subject is driven to the limits of his response range (by a large stimulus range or a poor choice of modulus, for example), the result is not always a discontinuity in the corresponding function at one of the limits; instead, the subject may redistribute his responses, yielding an overall flattening of the function. Kryter (1946) obtained flat noise-compensation functions, slope 0.33, when his speakers read word lists without correction in noise levels that reached about as high as Pickett's (105 dB, SPL). In a second part of the experiment, Kryter's speakers wore earplugs, probably increasing bone conduction of speech (occlusion effect: Hood, 1962; Békésy, 1960) while attenuating sidetone and ambient noise. The net effect was a drop of voice level from one to two decibels and no change in slope (broken line, Figure 1). (The same effect of earplugs on voice level was reported by Hebb, Heath, and Stuart in 1954.)

The ceiling effect is evident in the remaining noise-compensation function in Figure 1 (Hanley and Steer, 1949), which was obtained with even higher noise levels than those used by Pickett and Kryter. With the first 5-dB increase in earphone noise (101-106 dB, SPL), the speakers raised their vocal levels approximately half as many decibels. With each successive increase in noise, however, there was a smaller compensatory increase in vocal level, "as the subjects' limits of response potentialities are approached" (p. 368).

Bearing in mind these influences of the premium on intelligibility and the range of criterion levels, the studies of speech communication in noise summarized in Figure 1 confirm Lombard's claim that voice level increases with increasing noise level. They also show that the Lombard function is, in particular, a power function with exponent (slope) one-half; a given decibel increase in noise level will evoke, at most, half as great an increase in the speaker's voice level.

DYNAMIC RELATIONS BETWEEN HEARING AND SPEAKING

Noise Compensation and Sidetone Compensation

Lombard believed that the increase in voice level caused by loud noise and the increase caused by reduced sidetone in patients with perceptive hearing loss 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 . . ." (1911, p. 101).

Black (1951b) performed an experiment that permits us to evaluate this significant claim. He measured the effect of sidetone reduction on speaking level by inducing temporary threshold shifts. He subjected 144 male college students to two hours of noise at 110 dB (SPL) and then measured, at three-minute intervals after the termination of the noise, both hearing loss and the increase in voice level during the reading of phrases. Black found that, on the average, a 10-dB increase in threshold caused a 5.7-dB increase in voice level. This is just a little more than would be caused by a 10-dB increase in noise level, according to Webster and Klumpp. A dozen years earlier, Rubenovitch and Pastier (1938) also reported parallel effects for noise and sidetone reduction, although they could only obtain one value of sidetone reduction by inserting cotton plugs in the ears.

Thus, loud noise and hearing loss do appear to have related effects, as

Lombard believed. A much more stringent interpretation of Lombard's statements yields the following hypothesis: noise compensation and sidetone compensation reflect the same underlying process; the two functions have the same form and are merely complements. In order to evaluate this hypothesis, Figure 2 assembles the results of 10 studies of sidetone compensa-

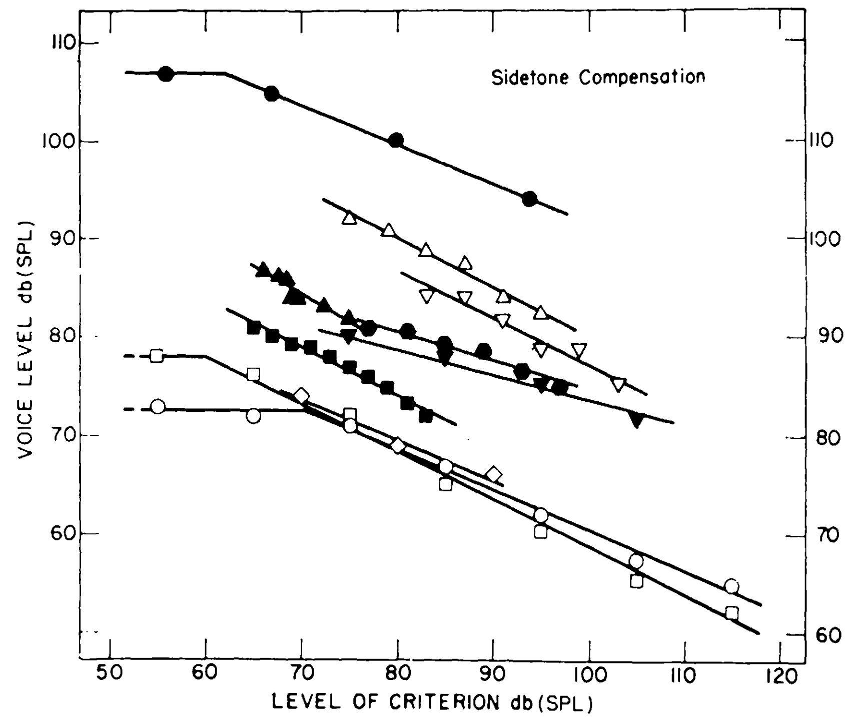

FIGURE 2. Sidetone-compensation functions obtained in 10 experiments when speakers adjusted their autophonic levels to compensate for changes in their sidetone loudness, with or without instructions to do so.

tion under monaural and binaural conditions. A glance at the figure shows that sidetone feedback has a continuously variable effect on voice level, the inverse of the effect of noise. As the earlier discussion of the Lombard test anticipated to a degree, monaural alterations in sidetone evoke smaller changes in voice level than do binaural alterations. Speakers compensate in this fashion quite reliably under instructions to do so or, as in the case of the Lombard function, without any such instructions, quite unconsciously.

The slopes of the sidetone-compensation functions obtained in the various studies are listed in Table 2. In their experiment, Lane, Catania, and Stevens (1961) used a sidetone circuit, consisting of a microphone, an amplifier, and a binaural headset that attenuated airborne sound some 20 dB, to feed the speaker's voice back to him at levels from 20 dB below to 40 dB above standard

TABLE 2. The slopes of sidetone-compensation functions obtained in experiments with diverse conditions and tasks, Figure 2.

Experimenters	*Conditions and Tasks*	*Figure Symbols*
	Binaural	
Black (1951b)	Reading phrases during temporary hearing loss	−0.57 ▲
Lane, Catania, & Stevens (1961)	Holding sidetone loudness constant while vocalizing a vowel	−0.46 □
	Vocalizing the modulus for autophonic scaling	−0.41 ◇
Licklider & Kryter (1944)	Reading sentences over interphones:	
	5,000 ft	−0.50 △
	35,000 ft	−0.46 ▽
Lightfoot & Morrill (1949)	Reading word lists over interphones, ground	−0.41 ●
	Monaural	
Lane, Catania, & Stevens (1961)	Holding sidetone loudness constant while vocalizing a vowel	−0.40 ○
Fletcher, Raff, & Parmley (1918)	Reading monosyllables into a telephone	−0.25 ▼
Noll (1964a, b)	Reading passages into a telephone	−0.30 ⬢
McKown & Emling (1933)	Conversing during business telephone calls	−0.49 ■

sidetone, in 10-dB steps. Each of 10 speakers was instructed to hold the loudness of his voice constant, as he perceived it, during productions of the vowel /a/. The sidetone-compensation function was found to have a slope of − 0.46. When sidetone was varied only monaurally, the compensation function was, not surprisingly, flatter: − 0.40. Under this monaural condition, which prevails in studies of telephonic sidetone penalty, the subject can still hear his voice binaurally; the sidetone is changing in one ear, and it is constant in the other; the net change in sidetone may be less than the monaural change, therefore. Furthermore, the monaural loudness scale is a little flatter than the sone scale: slope 0.54 versus 0.60 (Reynolds and Stevens, 1960).

In probably the earliest study of sidetone compensation, contemporary with Lombard's complementary research, Fletcher, Raff, and Parmley (1918) instructed 60 speakers to read monosyllables at a conversational level into a telephone microphone under monaural sidetone amplifications ranging from 0 to 30 dB. Nearly half a century later, Noll (1964a,b) had telephone talkers read prepared passages under similar monaural conditions. The sidetone penalty functions, which we propose to call Fletcher functions, were found to have slopes of − 0.25 and − 0.30, respectively. In both studies, neither binaural listening nor a communication task was employed, and the effects of sidetone on voice level seem to have been attenuated accordingly. In contrast, McKown and Emling (1933) monitored actual 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.

Additional measures of binaural sidetone compensation come from wartime tests of aircraft interphones and from a scaling experiment. When the gain of an interphone is varied, this varies the power delivered to all headsets, and hence the speaker's sidetone is altered. Licklider and Kryter (1944) had speakers read sentences over an interphone during flights at 5000 and 35,000 feet, while Lightfoot and Morrill (1949) conducted a similar experiment with word lists on the ground. The Fletcher function was found to have slopes of − 0.50, − 0.46, and − 0.41, respectively. This function was also determined quite incidentally in the course of measuring the effect of augmented sidetone on the slope of the autophonic scale. Lane, Catania, and Stevens (1961) 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. Completing this brief survey of Figure 2, we come back to Black's results (1951b) for sidetone reduction obtained by temporary deafening, which were described earlier and are shown by the filled triangles; the Fletcher function has a slope of − 0.57.

Figures 1 and 2 taken together show that, to a good approximation, the stringent interpretation of Lombard's hypothesis is correct; just as speakers compensate only halfway in decibel units for increases in the ambient noise during communication, so they compensate, at most, halfway for decreases in their apparent speaking level. Noise and sidetone compensation seem to be two sides of the same coin.

Noise and Sidetone Compensation Viewed as Cross-Modality Matching

If noise and sidetone compensation are both reflections of the same underlying process, it is natural to ask next what this process might be. Lombard stated that an adequate explanation of the Lombard sign was not to be found in the hypothesis of a mere loss in auditory feedback control, as this alone does not explain why there should be a systematic increase in voice level. Nor does it explain why voice level decreases under reduced noise and, even more crucially, under increased sidetone, where there is no question of a loss in auditory feedback. Lombard believed instead that the changes in voice level, both under increased noise and reduced sidetone, reflected "un effort d'adaptation à des conditions nouvelles . . ." (p. 112). In particular, the speaker "se crie en quelque sorte à soi-même, comme on crie à l'oreille d'un sourd" (1911, p. 112). This formulation puts the emphasis on communication where, we have seen previously, it properly belongs. The speaker raises his voice in order to be understood. An increase in the ambient noise or a decrease in the level at which he is heard yields a reduction in the signal-to-noise ratio of his communication, and the speaker who fails to compensate will typically suffer a loss in intelligibility.

The hypothesis may be put explicitly as follows: during communication, the speaker undertakes, at most, to compensate fully for changes in the signal-to-noise ratio, which governs his intelligibility; he matches apparent changes in the signal level inversely and apparent changes in the noise level directly.

If this hypothesis is correct, then a subject told to imitate changes in the level of a noise or of a speech signal will match a fourfold increase in the criterion with only a twofold increase in voice level—just as he does when compensating for noise or sidetone changes. In other words, if both noise and sidetone compensation are matching phenomena, and both functions are straight lines with slope 0.5 (absolute value), then the matching function should turn out to be a straight line in decibel coordinates with a slope of 0.5.

There is an independent and more interesting way to arrive at a prediction of the form of the matching function, based on analyzing in turn the processes that underlie matching. The experimenter presents a criterion sound at several sound pressures (P_c). The subject matches each change in loudness (L) with a change in voice level of the same magnitude, as it seems to him. Let us call this his autophonic level (A). The experimenter notes, in turn, the sound pressure of each vocal production (P_v). Now if the sound pressure of the criterion were linearly related to its loudness ($P_c \sim L$), and if the subject's autophonic level were linearly related to the sound pressure of his voice ($A \sim P_v$), then in matching a change in criterion loudness with one in autophonic level ($L \sim A$), the subject would equate the increase in criterion sound pressure with an increase of the same size in voice sound pressure ($P_c \sim P_v$). Doubling the criterion level, for example, would cause the subject to double his voice level; the matching function would have a slope of 1.0. Of course, it seems a priori quite improbable that the sensory operating characteristics for speaking and listening should both be linear or, more generally, grow at the same rate. The speaker judging his own voice level has proprioceptive as well as acoustic information to go by; when judging the ambient noise, or someone else's voice level for that matter, he has only acoustic cues available. In fact, for a subject to perceive a doubling in loudness, the sound pressure 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 known as the *sone scale* (Stevens, 1955); the latter relation is becoming known as the *autophonic scale,* a term coined by Lane, Catania, and Stevens (1961).

Restated as equations—in which constants governing the size of units are ignored—the two sensory scales have the following form:

$$L = P_c^{0.6} \qquad \text{and} \qquad A = P_v^{1.2}$$

In matching, the subject equates A and L at various levels. It follows that P_v will be related to P_c in this way:

$$P_v^{1.2} = P_c^{0.6} \qquad \text{or} \qquad P_v = P_c^{0.5}$$

In decibel coordinates, $P_v = 0.5\ P_c$: that is, the matching function is predicted to be a straight line with slope 0.5. Since noise and sidetone compensation are indeed described by functions with this form, our hypothesis that they are fundamentally matching processes receives indirect confirmation. This derivation 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 (Stevens, Mack, and Stevens, 1960). Although consistent with the results for noise and sidetone compensation, the predicted outcome is somewhat surprising; a listener presented with a fourfold increase in sound pressure will match it with a twofold increase in his voice level. In other words, the 1:2 disparity between the slopes of the sone and autophonic scales yields a matching function that is linear in decibel coordinates with a slope of one half.

This prediction is generally borne out by the results of several studies (Table 3) whose matching functions are assembled in Figure 3. In one experiment, Lane, Catania, and Stevens (1961) employed 10 subjects, the vocal response /a/, and a noise that ranged over 50 dB in 10-dB steps. The matching function had a slope of one-half. When Lane (1962) had nine speakers imitate the disyllable /baba/ pre-recorded with varying degrees of iambic or trochaic stress, he obtained a stress-matching function with a slope of 0.54.

For reasons unknown, Black (1955) obtained rather steeper matching func-

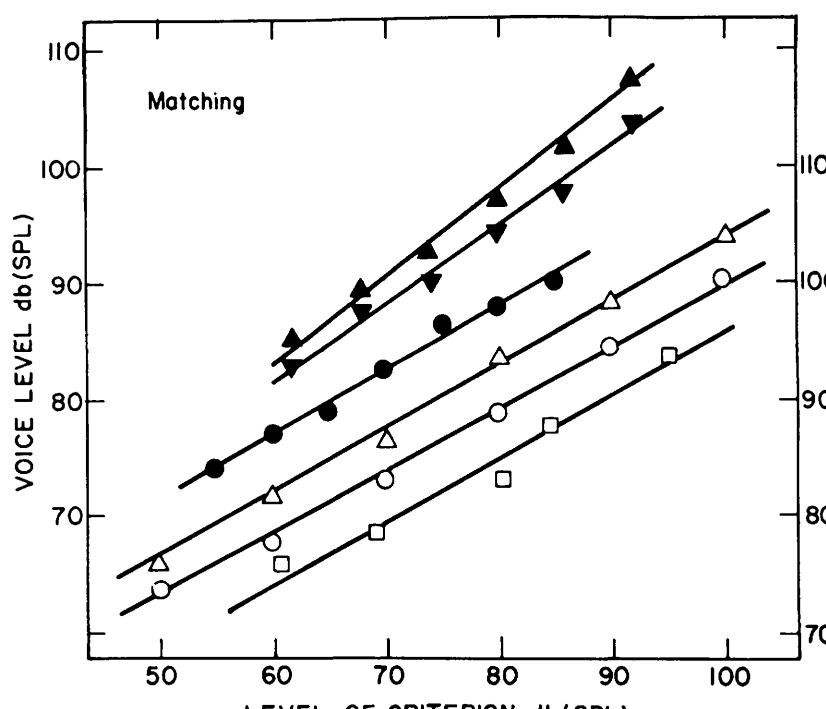

FIGURE 3. Matching functions obtained in several studies when speakers matched their autophonic levels to changes in the loudness of criterion sounds.

TABLE 3. The slopes of matching functions obtained in experiments with diverse conditions and tasks, Figure 3.

Experimenters	Conditions and Tasks	Figure Symbols
Lane, Catania, & Stevens (1961)	Matching a vowel to noise from loudspeaker earphones	0.51 ○ 0.52 △
Lane (1962)	Imitating disyllables with varying stress	0.54 ●
Black (1955)	Matching a monosyllable to noise To a sweep frequency tone	0.73 ▲ 0.67 ▼

tions, slopes 0.73 and 0.67, when he asked each of 24 speakers to utter the word *top* at the same loudness as that of a noise or a sweep-frequency tone whose levels varied over 30 dB. The last function in Figure 3 comes from the converse of a matching experiment; Irwin and Mills (1965) measured "pairs of sensations corresponding to equal stimuli . . . instead of measuring 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 predicted slope of the function relating autophonic levels to loudness estimates was 0.50; the obtained slopes were 0.53 and 0.52 for two groups of subjects. Although the results are in subjective rather than physical units, the former function is shown converted to decibels for comparison (squares).

The evidence from Figures 1, 2, and 3, considered together supports the lead taken from Lombard at the start of this section. The Lombard sign (Figure 1) and sidetone compensation (Figure 2) are the result of matching autophonic level to noise or to speech loudness (Figure 3). During communication, the speaker makes these matches to compensate for changes in signal-to-noise ratio. He matches his voice level inversely to apparent changes in signal level and directly to changes in the noise level. A perfect match is achieved subjectively when the compensation has succeeded only halfway objectively (Figures 1 and 2). This is because the loudness of the criterion grows only half as fast as the loudness of one's own voice; the sone scale has half the slope of the autophonic scale (Figure 3).

The findings that have led us to recognize the functional equivalence in communication of the Lombard sign, sidetone compensation, and matching have come from disparate studies of these three processes conducted under widely divergent conditions. Recently, however, Lane, Tranel, and Sisson (1970) have measured all three functions, as well as the sensory operating characteristics that govern them, with the same pairs of subjects communicating under the same conditions. Their results, shown in Figure 4, provide a tidy confirmation of the three-way functional equivalence. Using a procedure that placed a premium on intelligible communication, these investigators obtained Lombard and Fletcher functions with the same slope, one-half, just as predicted, and a matching function that was a little steeper than expected, 0.59. Nicely enough, the sone and autophonic functions for the same group of

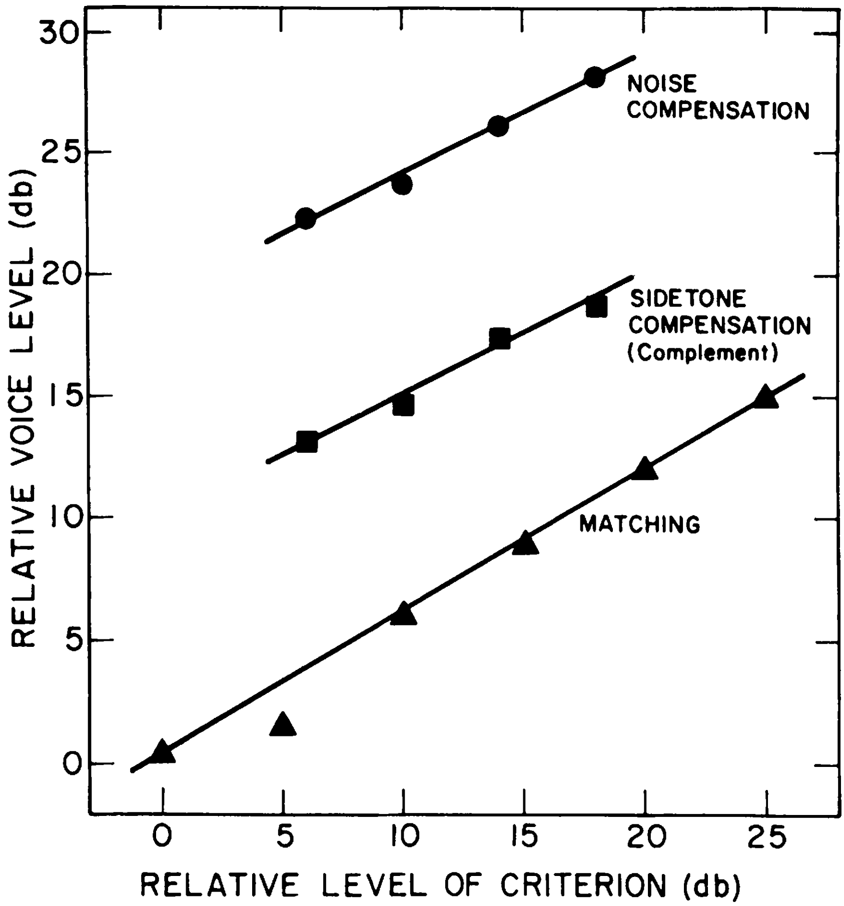

FIGURE 4. Effect on voice level of (1) changes in the level of a sound that speakers were instructed to match, (2) changes in sidetone amplification during communication over an interphone, and (3) changes in noise level during communication over an interphone. (The complement of the sidetone-compensation function is drawn to facilitate comparison with the matching and noise-compensation functions.)

subjects turned out to have slopes of 0.62 and 1.2, respectively, or a ratio of 0.52, quite in accord with the compensation and matching results.

This final evidence for the communication role of the Lombard sign, for its functional equivalence with sidetone compensation and matching during speech transmission, leads us to the implications of Lombard's research for the theory of the speech mechanism as a servomechanism.

THE LOMBARD SIGN AND THE SERVOMECHANISM MODEL OF SPEECH

We have seen that the function of the Lombard sign, like that of its complement, sidetone compensation, is to compensate for reductions in the signal-to-noise ratio so as to maintain effective communication. Indeed, the extent of this compensation depends on how demanding the communication situation is. Black has put it well: "The satisfactory rate and level may vary with the magnitude of the speaking situation, possibly the degree of responsibility that the speaker feels, etc." (1954, p. 144; 1949c). Clearly, to view noise and sidetone compensation as fluctuations in the feedback loop of a self-contained, self-regulatory speaking system is to miss their crucial characteristic, their communication function. They are, so to say, not inner-directed but other-directed; the speaker does not change his voice level to communicate better with himself, but rather with others. "This quasi-reflex self-regulation of the speaking voice is. . . . primarily hearer directed" (Hermann and Fónagy, 1958, p. 180). "We tend to maintain a favorable margin between the loudness of our speech and the background noise. We thus achieve intelligibility without talking so that our listeners find our speech unpleasantly loud" (Carhart, 1947, p. 306).

Nevertheless, numerous authors have misread the Lombard sign as evidence that the speaking mechanism is a servomechanism controlled by auditory feedback. For example, Lombard's contemporary Kerrison (1918) wrote, "[The test] depends upon the fact that to the normal man the sound of his voice is necessary to the proper regulation of its tone and intensity" (p. 664). Scal said exactly the same thing in 1926 (p. 239) and Grove in 1943 (p. 576). Similarly, Halphen (1910a,b), Becker (1932), Moulonguet (1933), Azzi (1956), Egan (1967), Iwamura (1967), and Charlip and Burk (1969) all believed that hearing the voice is necessary for its intensity regulation. Moulonguet, for example, wrote, "Si ce sujet normal est assourdi par un bruit violent, il n'entend plus sa voix et, instinctivement, augmente l'intensité de l'émission . . ." (1933, p. 14). According to Husson (1954), the increase in voice level in noise is indeed a "cochleo-recurrential reflex." Rubenovitch and Pastier (1938) also saw the Lombard sign as a "réflexe conditionnel." Lombard himself seems to have favored the servomechanism interpretation of his sign when he compared the Lombard sign with vestibular reflexes and wrote,

> L'appareil cochléaire . . . est le point de départ d'une action accommodative compliquée, dont l'aboutissant est à la musculature thoraco-laryngée. Cette action commande le mécanisme de l'adaptation vocale (p. 114).

However, Lombard did credit noise compensation with public as well as private functions, stating that it was "nécessité par l'obligation de se faire mieux entendre d'un interlocuteur" (p. 101)—as well as by oneself.

In retrospect, it is easy to see that Lombard gave a lot of thought to the effects of increasing noise and decreasing sidetone and their relations, but no thought to the effects of decreasing noise and increasing sidetone and their relations. The latter set of operations—moving down rather than up the noise and sidetone compensation functions—would have revealed, however, one of the difficulties of the servomechanism explanation of changes in voice level. Why, if the function of these changes is "de s'entendre mieux soi-même" (Lombard, 1911, p. 101), does the voice level drop under reduced noise or enhanced sidetone? Several other questions are left unanswered by the interpretation of noise and sidetone compensation as self-addressed reflections of the normal auditory autoregulation of speech. If the effect of noise or sidetone attenuation is solely to interrupt auditory feedback control of the voice, why doesn't voice level fluctuate uncontrollably under these conditions, rather than increase systematically (Lombard, 1911; Hebb, Heath, and Stuart, 1954)? Why is there an increase in voice level under monaural presentation of noise, when feedback control could be carried out with the other ear? Why does the change in voice level depend on whether the speaker is really communicating with an audience (premium on intelligibility)? Why does the Lombard function have the same form and exponent as sidetone compensation and matching to an external criterion? Why is fluent speech possible under complete binaural masking, or again after traumatic deafening, when sidetone control of speaking is not possible? Why does the Lombard sign adapt out with repeated presentations of an increase in the ambient noise (Fónagy and Hermann, 1964; Lombard, 1911)?

If the Lombard sign and sidetone compensation are not evidence that the speaking mechanism is a servomechanism employing auditory feedback for normal autoregulation, could it be that, after all, auditory feedback has no such role? The defining characteristic of a servomechanism is that a sample of the output of the mechanism is fed back to some point where it controls the ensuing output (Brown and Campbell, 1948). The returning information may be used to trigger successive steps in a series of events, to keep an activity functioning within predetermined limits (negative feedback), or to promote more of the same type of activity (positive feedback). The servomechanism has been invoked as a model for many human activities and functions—for example, respiration and thermal homeostasis. The relevant questions here are whether the production of speech is controlled by information fed back from the output and, if so, whether this information is in part auditory (exteroceptor) or not (interoceptor). The currently accepted application of the servomechanism model to speech production puts the emphasis on autoregulation by auditory feedback control. For example, Fairbanks' classic article on this topic states, "When I say a word and you repeat it, your hearing apparatus measures my word for purposes of estimation and then your word (the same word) for purposes of control" (1954, p. 135). Piaget put it about the same way in 1948 (p. 74) and Rutherford in 1967 (p. 247). The Lombard sign and sidetone compensation are nearly always construed as favoring this sidetone control hypothesis. The following sections present evidence, on the contrary, that sidetone is not used to control normal speech fluency and that, indeed, the use of sidetone is associated more with the perturbation of speech. Thus, these findings rejoin those presented in the preceding sections, indicating that auditory monitoring is used largely to maintain effective communication under varying external conditions.

In applying the servomechanism model to speech production, an internal or private loop is recognized first; this loop, for direct feedback control during speech, is served by interoceptors, particularly those that transduce touch and bodily movement (Lane, 1970; MacNeilage, 1970). This is the primary loop, permitting monitoring of both the productive mechanism and the regulatory mechanism—that is, the compression of the respiratory bellows on the one hand, and the nature and degree of constrictions introduced into the airstream on the other. Interruption of only a small part of the private loop, by nerve-block anesthesia of the oral cavity for example, causes large increases in articulation errors (Ringel and Steer, 1963; Ladefoged, 1967; MacNeilage, Rootes, and Chase, 1967). Masking or other sidetone distortion is less disruptive than tampering with the private loop (Schliesser and Coleman, 1968; Ringel and Steer, 1963; McCroskey, 1958). Contrary to received opinion, the private loop is quite sufficient to permit precise changes in voice level on command; the autophonic function of congenitally deaf subjects is no different from that of normals, or normals subjected to intense masking (Lane, 1963). The private loop is also quite sufficient to provide whatever feedback is needed to maintain fluent articulation after experimental or traumatic deafening (Sedlacek, 1950; Chesni, 1960; Pickett, 1958; Dreher and O'Neill, 1958).

"We speak with our ears," aphorized Harvey Fletcher in his influential book *Speech and Hearing in Communication* (1953), thus assigning to sidetone a fundamental role in directly regulating speech. But "We speak with our sense of touch" would be closer to the truth, thus emphasizing the private loop and the role of interoceptive feedback in the regulation of ongoing speech. Or again, "We learn to speak with our ears" would be accurate, thus emphasizing the role of feedback from an audience in shaping the phonological repertoire. And it would be closer to the example Fletcher goes on to cite: the congenitally deaf child who does not easily learn to speak.

The preceding evidence for the role of the private loop should not be interpreted to mean that each successive segment of speech is controlled by the interoceptive feedback from the last segment; temporal considerations seem to require a larger provision for preprogramming (Kozhevnikov and Chistovich, 1966; Lashley, 1951). For example, birds that are deafened go on producing their various calls undisturbed (Konishi, 1965; Nottebohm, 1966). This shows that the vocalizing does not require auditory feedback, but we should not conclude that it therefore depends on the private loop, since the birdcalls are probably extensively "preprogrammed."

Of course, the deafened speaker cannot remain indefinitely cut off from normal feedback from his audience without this affecting his communication. This calls our attention to another feedback loop that is basic to speech communication, the external or public loop, which requires mediation by another person. In contrast with the private loop, it is served by exteroceptors and may be used for indirect self-monitoring; it permits the speaker to observe the consequences of his speech on the vocal and nonvocal behavior of his audience, and to regulate his speech accordingly (in general, unconsciously). The public loop can be seen at work most simply and quantitatively when we adjust our voice level to that of the person with whom we are speaking,[5] or raise our voice for a distant listener and lower it for one at hand. Black (1949a,b) showed that speakers who are answering questions or repeating messages tend to adjust their level to that of the person with whom they are speaking—even if asked not to (also see Baird and Tice, 1969). Lombard's best student, Baldenweck, developed a test to detect auditory malingering based on this tendency to regulate voice level over the public loop (Baldenweck, 1934). Similarly, the speaker's rate, inflection, and precision of articulation are all controlled over the public loop by those of his conversational partner (Black, 1950b; Lightfoot and Black, 1948). But the public loop is also the medium for much more subtle phenomena of language acquisition and use, including learning the sound system of one's language.

Functioning to preserve intelligible communication with an audience and readily controlled by audience variables, noise and sidetone compensation might seem to belong to the public loop. This is an incomplete analysis, however, because the Lombard and Fletcher functions can be obtained from a speaker in the absence of a responsive listener. What then is the feedback loop? In these special cases, the public loop is effectively short-circuited; the exteroceptors are used for direct self-monitoring. When we are speaking on the telephone and static occurs on the line, we may unconsciously raise our voice without waiting for a misunderstanding or for the other person to raise his voice. We have short-circuited the public loop, but only because if the speech-to-noise ratio is not restored, this usually leads to impaired communication over the public loop. Similarly, if we are speaking from the stage of an auditorium and the loud speakers return the speech to the stage too loudly, we will lower our voice; too softly, we will raise it; too late, and we will try to compensate for this temporal distortion. In a "dead" hall that absorbs sound energy we speak more loudly, while in a live hall that reflects sound energy we speak more softly (Black, 1950a; Black and Tolhurst, 1956). In each of these cases, we do not and need not await deviations in the behavior of the audience over the public loop. In each case, anomalous circumstances cause us to short-circuit the public loop, to monitor our speech directly with our ears, and to make some adaptive change.

We have suggested that auditory self-monitoring is a response to altered communication situations that develops from the use of the public loop for effective and efficient speech communication. Several theories of speech

[5]Jakobson (1968) suggests that this use of the public loop is a milestone in the socialization of the child: "There arises and grows by degrees in children a desire for communication. We witness the first expressions of his social life: the child seeks to respond to and adapt himself to the person to whom he is speaking in every way, even in changes of volume" (p. 24).

acquisition that are not ostensibly servomechanism theories implicitly take quite a different stand, however. They presuppose continual sidetone monitoring, if not control, during speech—and that from the very outset of language acquisition.

The first of these, the motor theory of speech perception, thus turns out not only to assign speaking a fundamental role in listening, but also to assign listening a fundamental role in speaking. Its name comes from the former claim, more generally, that speech decoding is accomplished by reference to encoding (for a critical discussion see Lane, 1965, and Studdert-Kennedy et al., 1970). But the correspondences between the sound pattern to be decoded and the encoding gestures in the speaker's particular language must be acquired previously. Thus this theory is obliged to assume at least that the speaker monitors his own sidetone: "We know that the temporal overlap of these activities exists as an ever present consequence of the fact that people listen while they speak" (Liberman et al., 1968, p. 29).

A long-abandoned theory of language acquisition, the circular-reflex theory (Holt, 1931; Allport, 1924; Smith and Guthrie, 1923), was also based on this hypothesized temporal overlap of speech production and sidetone monitoring. The theory was obliged to posit in addition a kind of backward Pavlovian conditioning (Lane, 1970; Greenwald, 1970): "Infants which are born deaf do not learn to speak . . . because a prerequisite to the acquisition of speech is the establishment of reflex paths . . . such that a sound received at the ears causes the vocal organs reflexly to produce that sound" (Holt, 1931, p. 39).

Autism theory (Mowrer, 1950), although based on a different conditioning mechanism, also seems to require auditory self-monitoring for acquiring one's native language. These hypotheses are opposed, however, by the reported ability of tracheotomized and autistic children who did not vocalize at first in infancy to later take up vocalizing appropriate to their age level (Lenneberg, 1967), as well as by the absence of delayed auditory feedback effects in infancy (Cullen, Fargo, and Baker, 1968). Probably, children need to learn to monitor others and then themselves at the expense of failures in communication.[6]

The sidetone control hypothesis requires not only that the speaker listen to his speech continuously, which seems to be disconfirmed by the evidence, but also that this sidetone actively controls his ensuing speech. The hypothesis of a direct link between ear and voice was advanced first by de Cordemoy in 1668 and advocated more recently under the name "cochleo-recurrential reflex" in physiological studies by Garde and Chevrie-Muller (1967); Garde (1965); Stromsta (1959); Vannier, Saumont, Labarraque, and Husson (1954);

[6]"We see ourselves as others see us . . . In the case of the vocal gesture, the form hears its own stimulus just as when this is used by other forms, so it tends to respond also to its own stimulus as it responds to the stimulus of other forms . . . That the person should be responding to himself is necessary to the self and it is this sort of social conduct that provides behavior within which the self appears" (Mead, 1934, pp. 63, 139).

and Husson (1951). Tomatis takes a very strong position here: not only is phonation controlled by audition (1956), but even "la voix d'un sujet ne contient que les harmoniques que son oreille est susceptible d'entendre" (1960, p. 197). He goes on to false or unlikely conclusions about such diverse human concerns as singing, musicianship, stuttering, sound localization, traumatic hearing loss, comparative phonetics, and second-language learning (Fournier, 1962; Lafon, 1966). From this point of view, the Lombard sign is not evidence of a sidetone control loop (since no link from voice to ear is also hypothesized), nor of a public loop (the demands of efficient communication are not discussed), but simply of overstimulation of the cochleo-recurrential reflex (Garde, 1965).

However, many experimenters have failed to find evidence of a true ear-voice reflex and have faulted the previous research on methodological grounds (Molinari and Pivotti, 1963; Fónagy and Hermann, 1964; Arslan, 1964; Morgon, Lafon, and Prelot, 1964; Van Michel and Le Maire, 1965, 1967). We can be rather confident that the Lombard sign is not mediated by a cochleo-recurrential reflex, since speakers without a larynx emit the sign (while speaking in fake whisper or belch voice; Panconcelli-Calzia, 1958). Indeed, it seems so much more reasonable to assume that the esophageal speaker, like the normal one, speaks louder in noise in order to be understood. The complementarity of noise compensation and sidetone compensation also militates against an explanation of the former as the result of auditory hyperstimulation of an ear-voice reflex. Garde (1965) was naturally misled to this explanation when he found that noise increased voice level but earplugs did not. He was apparently not aware of the results obtained by Rubenovitch and Pastier (1938) also using earplugs, nor of more systematic studies of sidetone attenuation, nor of the occlusion effect—all cited previously. Panconcelli-Calzia's finding (1955) that fewer patients with psychogenic voice disorders emit the Lombard sign than normal speakers or those with functional or organic voice disorders also indicates that the Lombard sign is simply not a purely peripheral or subcortical reflex. The link between listening and speaking is a matter of conditioning, of learning to use the public loop, rather than of physiology alone.

Disruption of Speech by Sidetone

In a particularly explicit statement of the sidetone control hypothesis, Fry contends that "the distance that the tongue moves, the speed at which it moves, the exact moment at which it changes direction—all these are determined largely on the basis of information supplied by the auditory feedback" (1957, p. 444). Now the sequencing of speech segments through auditory feedback is inconsistent with timing considerations (Kozhevnikov and Chistovich, 1966; Lenneberg, 1967) as well as with all that has been argued here previously. Fry himself reminds us of the most direct of these arguments when he notes later in the same article that speaking can continue normally despite masking (when only the interoceptors are providing information). Then, we may ask, why assign a function to sidetone at all? Fry writes, "The fact that the complex and exact timing in speech is very much dependent on auditory feedback is demonstrated by the effects of 'delayed feed-back'" (1957, p. 444). Similarly, the effects of delayed auditory feedback are the clincher for Dupon-Tersen (1953), "the most elegant demonstration to date of the ear-voice servomechanism control of speaking" (p. 98).

In general, the sidetone control hypothesis seems to have won credence because distorting a speaker's sidetone perturbs his speech. The Lombard and Fletcher signs are construed as confirming the hypothesis because they demonstrate an effect of distorting the intensity parameter, while the Lee effect (cited by Fry and Dupon-Tersen) demonstrates the effect of distorting the temporal parameter. The counter arguments and findings presented in this section cluster around three themes. First, the more salient the distorted sidetone cues, the more the perturbation of normal speech, and the less salient, the less the perturbation. This shows that sidetone cannot be the sole or even predominant control signal in speech production. Second, the finding that distorted sidetone perturbs speech does not show that normal sidetone controls normal speech. Third, the effects of sidetone distortion are those appropriate to the public loop, suggesting that the distortion is effective not because of sidetone autoregulation of speech but because of the demands of intelligible communication under such distorted conditions.

Far from confirming that "we speak with our ears," the Lee effect demonstrates the impossibility of bringing fluent speech under exclusive control of hearing. The way in which delayed sidetone disrupts speech deserves a closer look in this perspective. (For reviews of the literature, see Chase, Sutton, and First, 1959; Yates, 1963; Fargo and Armacost, 1968.) Although tactile and proprioceptive feedback constitute the primary loop, they are normally accompanied by correlated auditory feedback, which is delayed about 1 msec in the case of airborne sidetone and about 0.4 msec for bone-conducted sound (Stromsta, 1962). These sidetone cues may compete with the interoceptive cues in controlling the progress of speaking (Huggins, 1968)—if they are made salient enough. Under these conditions, sidetone delays longer than normal produce slower rates of speaking (Huggins, 1968), while those faster than normal enhance the rate (Peters, 1954; Davidson, 1959). Distorted sidetone delays not only disrupt the rate of speaking and elicit autonomic responses (Haywood, 1963),[7] they also produce articulation errors, higher fundamental frequency, and increased sound pressure level (Lee, 1950; Black, 1951a; Fairbanks, 1955; Chase, Sutton, and Rapin, 1961; Zalosh and Salzman, 1965; Ham and Steer, 1967). The latter increase in voice level may be partly a Lombard effect, with the speaker's voice serving as the noise signal. The

[7]Subjects who are made to listen to their own sidetone tape-recorded, also find this arousing and disturbing, according to various physiological and projective measures (Holzman and Rousey, 1966; Holzman, Rousey, and Snyder, 1966; Rousey and Holzman, 1968).

Azzi test (1951; Tiffany and Hanley, 1952) uses the increase in level, along with the other disruptive effects of delayed sidetone, to detect auditory malingering: if the patient's speech is disrupted at low to moderate levels of delayed sidetone feedback, the otologist concludes that there is little or no hearing loss (Hanley and Tiffany, 1954). Most investigators consider the Azzi test an elaboration of the Lombard test (Wetterwald, 1955; Fournier, 1956).

The disruptive effects of sidetone are reduced, or course, when sidetone cues are less salient relative to interoceptive cues; for example, when sidetone intensity is less (Tiffany and Hanley, 1952; Butler and Galloway, 1957), when there is auditory masking (Singh, Brokaw, and Black, 1967), or when the speaker is resistant to using sidetone cues (Yates, 1965; Spilka, 1954; Goldfarb and Braunstein, 1958). If we say that, for the stutterer, sidetone cues are salient even when normal feedback relations are not distorted in their favor, then once again we find that the disruptive effects are less when sidetone cues are attenuated; stuttering is reduced by noise (Cherry and Sayers, 1956; Maraist and Hutton, 1957), by whispering (Cherry and Sayers, 1956), by auditory distraction (Cherry and Sayers, 1956), by deafness (Backus, 1938; Harms and Malone, 1939; Albright and Malone, 1942), and by high-pass filtering of sidetone (Cherry and Sayers, 1956).

Stuttering is also reduced by delayed auditory feedback (Webster, Schumacher, and Lubker, 1970; Lotzmann, 1961; Chase, Sutton, and Rapin, 1961; Nessel, 1958; Zerneri, 1966). This may be because the increased temporal separation of sidetone cues from interoceptive cues actually reduces rather than increases their conflict. Perhaps the lowered rate brought about by delayed auditory feedback assists the stutterer, or perhaps the stutterer's increased intensity indicates that the delayed feedback of his voice functions, like loud noise, assists the stutterer by obscuring his troublesome ongoing sidetone.

Consistent with the general suggestion that his own sidetone is peculiarly salient for the stutterer, Panconcelli-Calzia (1955) found the Lombard sign in only 27% of the stutterers he tested, as opposed to 70% of speakers with other voice disorders and 80% of normals. In sum, the stutterer's sensory disorder, if any, may be more in an excessive use of the short circuit, of sidetone cues, than in the temporally distorted information he is commonly purported to find there (Mysak, 1960; Tomatis, 1954). Perhaps stuttering reflects, in addition, a lack of some internal time-correction for the lag between sidetone and bone conduction, as Webster and Lubker (1968) have suggested, or maybe for the lag between auditory and interoceptive feedback. (For remarks on speech therapy and feedback, see Hartlieb, 1967; Butler and Stanley, 1966; Gruber, 1965; Mysak, 1959; and Shearer, 1959.) In any event, the experimental findings with stutterers and normals lead to the same conclusion: the less the sidetone monitoring, the more normal speech is possible.

The evidence that perturbations in sidetone can perturb speaking is not at all convincing proof of the sidetone control hypothesis for a second reason, one that generally constrains extrapolation from clinical data to normal functioning. The mode of operation in the abnormal state may supplant quite a different mode in the normal state. The ability of response correlated feedback to disrupt performance need not be predicated on a role for other values of that feedback in normal performance. For example, rhythmic key-tapping will be disrupted if each tap produces a light flash after a brief delay (Chase, Rapin, Gilden, Sutton, and Guilfoyle, 1961), but this does not show that visual feedback normally has a role in tapping. If the subject were instructed to ignore the delayed flashes, he could surely maintain normal rhythm, just as the subject instructed to ignore his delayed sidetone can maintain normal speech rhythm (Goldiamond, Atkinson, and Bilger, 1962). So, given that disrupted sidetone yields disrupted speech, it certainly does not follow that normal sidetone regulates normal speech. Far from it, the disruptions are effective only because in normal speech we have learned to use quite a different loop, the public loop, and to pay attention to the speech parameters of others. This may well be why perturbations such as delayed auditory feedback had no systematic effect on the vocalizing of infants in one study (Cullen, Fargo, and Baker, 1968), while the largest effects are obtained with children who are older and more advanced linguistically (Fargo et al., 1968; Yeni-Komshian et al., 1968; Chase, Sutton, First, and Zubin, 1961). And this would explain why the more remote the possibility of effective communication over the public loop, the less effective these sidetone perturbations are. Chase et al. (1967) have shown that delayed auditory feedback has no disruptive effects during psychomotor seizures in which speech continues normally. Mentioned earlier was Dreher and O'Neill's evidence (1958) that noise does not materially perturb the speaker's vocal level in the absence of an audience, real or imagined.

When there is an effect of sidetone perturbation, it is often precisely that appropriate to the public loop. Peters (1955) found that when a speaker's sidetone is filtered, he speaks more intelligibly. "This increase in intelligibility may result from the speaker's attempt to improve the precision which appears to be lacking in his own speech when the frequencies in the sidetone signal above 600 Hz are attenuated" (p. 375). Further evidence that the speaker reacts to changes in his sidetone as if they characterized the entire communication link comes from a study in which speakers read passages while listening to the same, unrelated, nonsense, or similar passages (Peters, 1956). The speakers were most intelligible in the last two conditions, when the danger of confusing the two message streams would be the greatest for a listener hearing both of them. It may well be that the changes in rate and articulation introduced by the speaker under delayed auditory feedback also have the effect of rendering the total auditory complex more intelligible.

The same result—better comprehension by the listener—is obtained if the speaker's sidetone is perturbed by noise or attenuation, instead of filtering or competing messages. The Lombard and sidetone-compensation functions reveal that the changes the speaker makes in his voice level under changes in noise or sidetone level are exactly those he would make if he were trying to maintain constant intelligibility of his speech for an active listener.

The changes in articulation that the speaker makes in noise were studied by Ladefoged (1967), who found alterations in vowel duration and intensity (as well as concomitant changes in pitch and quality). He attributed these changes to the lack of auditory feedback control in noise and to the stressful effects of noise, rather than to the natural aim of conversing intelligibly. Fónagy and Fónagy (1966) concluded, however, that these changes serve the interest of preserving intelligible communication to another, and Draegert (1951) indeed showed that of 13 phonetic variables affecting intelligibility in high noise, vowel intensity and duration were the most important.

There is a final bit of evidence along these lines from our ongoing research with speakers and listeners talking at various distances in noisy free fields. Our initial findings show that increases in the distance of the listener have the same effect on the speaker's voice level as comparable increases in the ambient noise level. If doubling the ambient noise, for example, has the same effect on the speaker's voice level as doubling the distance of his listener, it may well be because both operations cut the speech-to-noise ratio at the listener in half. Therefore, the speaker offsets the impending reduction in his intelligibility with the same increase in voice level in both cases. Since only one of these operations directly affects the speaker's ability to hear himself, while both affect the speaker's ability to be heard by his listener, clearly the results are not to be explained entirely by sidetone control of speaking.

Thus, all things taken together, the explanation of the Lombard sign lies neither in hypostimulation from the voice due to masking, as is generally believed, nor in hyperstimulation from the noise, as certain French investigators contend, but rather in accommodation to the demands of intelligible communication. Noise and deafness have the same effects on the speaker because they have the same effects on the listener; above all, they increase the minimum distinguishable speech signal (Radley, 1948). More generally, the evidence from experiments in which speaking is altered by sidetone changes merely reminds us how greatly speaking is controlled by the audience and is in the service of the listener over the public loop.

The preceding sections have shown that listening and speaking are not identical but quite different in their sensory dynamics, and that this difference regulates vocal imitation as well as communication with noise or sidetone alteration. This section has shown that listening and speaking are not interlocked but are quite separate temporally, and that we are no more obliged to listen to our own speech than to that of others. Ironically then, Lombard's work, the first to have studied the interdependence of speaking and listening, has led us after six decades of research to appreciate their independence and to recognize the basic differences between these two components of communication.

ACKNOWLEDGMENT

This article was prepared in part at the Center for Research on Language and Language Behavior of the University of Michigan, Ann Arbor (supported by contract no. OEC-3-6-061784-0508 with the U. S. Office of Education), and in part at the Institut d'Etudes Linguistiques et Phonétiques, Université de Paris, where the senior author is currently Visiting Professor. Bernard Tranel is now at the Department of Linguistics, University of California at San Diego. C. Sisson (University of Michigan) collaborated in much of the original research described here; remarks by S. Ross, (University of Copenhagen), and seminar papers by D. Pisoni (Purdue University) and E. Bouchard (Indiana University), among others, were highly instructive; we acknowledge their assistance with pleasure. The authors are also deeply indebted to the personnel of the Bibliothèque de la Faculté de Médecine, Université de Paris and to its Conservateur en Chef. Requests for reprints should be addressed to Bernard Tranel, Department of Linguistics, University of California at San Diego, LaJolla, California 92037.

REFERENCES[8]

*ACADÉMIE DE MÉDECINE, Séance du 12 Avril, 1910. *Bull. Acad. Méd.*, 63, 341, 351 (1910).

ALBRIGHT, M. A. H., and MALONE, J. Y., The relationship of hearing acuity to stammering. *Except. Child*, 8, 186-190 (1942).

ALLPORT, F. H., *Social Psychology*. Boston: Houghton Mifflin (1924).

*ALPERT, M., Feedback effects of hearing on voice level. Doctoral dissertation, New York Univ. (1965).

*ANON., ETIENNE LOMBARD. *Ann. Mal. Oreil. Larynx*, 41, 1 (1922).

*APPAIX, A., and OLIVIER, J. C., Le dépistage de la simulation en audiométrie. *Minerva Otorinolringol.*, 20, 155-159 (1970).

ARSLAN, M., Effets de l'excitation cochléaire sur l'activité bio-électrique du nerf récurrent. *Confin. neurol.*, 24, 74-79 (1964).

ATKINSON, C. J., Vocal responses during controlled aural stimulation. *J. Speech Hearing Dis.*, 17, 419-426 (1952).

*AUCOC, Mort de . . . M. le Dr. Lombard. Paris: Procès Verbaux, Conseil du Surveillance, Admin. Gén. Assistance Publ. Paris, 669 (1920).

AZZI, A., Le prove per avelare la simulazione di sorditá. *Riv. Audiolog. Prat.*, 5-6, 23-25 (1951).

AZZI, A., Il controllo auditivo della fonazione. *Riv. Audiol. prat.*, 6, 65-88 (1956).

*AZZI, A., Hearing test in simulation. *Int. Audiol.*, 1, 1-11 (1962).

BACKUS, O., Incidence of stuttering among the deaf. *Ann. Otol. Rhinol., Laryng.*, 47, 632-635 (1938).

BAIRD, J. C., and TICE, M., Imitative modeling of voice intensity. *Psychonom. Sci.*, 16, 219-220 (1969).

BALDENWECK, L., Le signe de l'imitation de la voix. Son utilisation dans le diagnostic des surdités simulées. *Pr. méd.*, 46, 942-943 (1934).

*BÁRÁNY, R., Noise apparatus for the detection of unilateral deafness. *J. Laryng.*, 23, 363-364 (1908).

*BÁRÁNY, R., Rectification. *Ann. Mal. Oreil. Larynx.*, 36, 110 (1910).

*BECKER, B. M., The Bárány noise apparatus. *Ann. Otol. Rhinol. Laryng.*, 41, 222-226 (1932).

BÉKÉSY, G. v., *Experiments in Hearing*. New York: McGraw-Hill, 128-147, 181-203 (1960).

*BÉRGÉR, W., Phonetische Untersuchungen über echten und vorgetäuschten postiven Ausfall des Lombardschen Versuches. *Mschr. Ohrenheilk.*, 66, 329-338, 440-447 (1932).

BLACK, J. W., The intensity of oral responses to stimulus words. *J. Speech Hearing Dis.*, 14, 16-22 (1949a).

BLACK, J. W., Loudness of speaking: The effect of heard stimuli on spoken responses. *J. exp. Psychol.*, 39, 311-315 (1949b).

[8]A search of more than six decades (1907-1970) of medical literature unearthed about four dozen articles citing or discussing the Lombard sign, usually in connection with hearing tests. All these references are marked * in the list. The principle sources searched were Index Medicus (1907-1970) and the Index Catalogue of the Surgeon General (Series 1-5).

Black, J. W., The relation between message type and vocal rate and intensity. *Speech Monogr.*, **16**, 217-220 (1949c).

Black, J. W., The effect of room characteristics upon vocal intensity and rate. *J. acoust. Soc. Amer.*, **22**, 174-176 (1950a).

Black, J. W., Some effects of auditory stimuli upon voice. *J. aviat. Med.*, **21**, 251-259 (1950b).

Black, J. W., Some effects upon voice of hearing tones of varying intensity and frequency while reading. *Speech Monogr.*, **17**, 95-97 (1950c).

Black, J. W., The effect of delayed sidetone upon vocal rate and intensity. *J. Speech Hearing Dis.*, **16**, 56-60 (1951a).

Black, J. W., The effect of noise induced temporary deafness upon vocal intensity. *Speech Monogr.*, **18**, 74-77 (1951b).

Black, J. W., Systematic research in experimental phonetics: 2. Signal reception: Intelligibility and sidetone. *J. Speech Hearing Dis.*, **19**, 140-146 (1954).

Black, J. W., Control of the sound pressure level of voice. Joint Project No. 42; Bureau of Med. and Surg., U.S. Navy Project No. NM 001 104 500.42 (1955).

Black, J. W., and Tolhurst, G. C., Intelligibility as related to the path of airborne sidetone. *J. Speech Hearing Dis.*, **21**, 173-178 (1956).

Bloch, A., Allocution du Docteur André Bloch. *Soc. franc. Oto-rhino-laryng.*, **47**, 57-67 (1949).

Brown, G. S., and Campbell, D. P., *Principles of Servomechanisms.* New York: Wiley (1948).

Butler, R. A., and Galloway, F. T., Factoral analyses of the delayed speech feedback phenomenon. *J. acoust. Soc. Amer.*, **29**, 632-635 (1957).

Butler, B. R., Jr., and Stanley, P. E., The stuttering problem considered from an automatic control point of view. *Folia phoniatr.*, **18**, 33-44 (1966).

Carhart, R., Conservation of speech. Ch. II in H. Davis (Ed.), *Hearing and Deafness.* New York: Murray Hill, 300-317 (1947).

*Chailkin, J., and Ventry, I., Functional hearing loss. In J. Jerger (Ed.), *Modern Developments in Audiology.* New York: Academic Press (1963).

*Charlip, W. S., and Burk, K. W., Effects of noise on selected speech parameters. *J. commun. Dis.*, **2**, 212-219 (1969).

Chase, R. A., Cullen, J. K., Jr., Niedermeyer, E. F. L., Stark, R. E., and Blumer, D. P., Ictal speech automatisms and swearing: Studies on the auditory feedback control of speech. *J. nerv. ment. Dis.*, **144**, 406-420 (1967).

Chase, R. A., Rapin, I., Gilden, L., Sutton, S., and Guilfoyle, G., Studies in sensory feedback: II. Sensory feedback influences on key-tapping motor tasks. *Quart. J. exp. Psychol.*, **13**, 153-167 (1961).

Chase, R. A., Sutton, S., and First, D., Bibliography: Delayed auditory feedback. *J. Speech Hearing Res.*, **2**, 193-200 (1959).

Chase, R. A., Sutton, S., First, D., and Zubin, J., A developmental study of changes in behavior under delayed auditory feedback. *J. genet. Psychol.*, **99**, 101-112 (1961).

Chase, R. A., Sutton, S., and Rapin, I., Sensory feedback influences on motor performance. *J. aud. Res.*, **3**, 212-223 (1961).

Cherry, C., and Sayers, B., Experiments upon the total inhibition of stammering by external control, and some clinical results. *J. psychosom. Res.*, **1**, 233-246 (1956).

Chesni, Y., Recherches sur l'activité phonatoire et articulatoire pendant la formulation verbale intérieure. *Rev. neurol.*, **102**, 706-718 (1960).

de Cordemoy, G., *Discours Physique de la Parole.* Paris: Florentin Lambert, 16-17 (1668).

Cullen, J. K., Jr., Fargo, N. L., and Baker, P., The development of auditory feedback monitoring: III. Delayed auditory feedback studies of infant cry using several delay times. *Ann. Rep. Neurocom. Lab., Johns Hopkins Univ. Sch. Med.*, 77-93 (1968).

Davidson, G. D., Sidetone delay and reading rate, articulation and pitch. *J. Speech Hearing Res.*, **2**, 266-270 (1959).

*DiCello, A. J., Deafness and its detection. *Ky. med. J.*, **41**, 168-171 (1943).

Draegert, G. L., Relationships between voice variables and speech intelligibility in high level noise. *Speech Monogr.*, **18**, 272-278 (1951).

Dreher, J. J., and O'Neill, J. J., Effects of ambient noise on speaker intelligibility of words and phrases. *Laryngoscope*, **68**, 539-548 (1958).

*Dupon, Y., Contribution à l'étude du contrôle de la phonation par l'audition. *Thès. Fac. Méd. Paris,* No. 539 (1952).
Dupon-Tersen, Y. R., Prédominance du circuit cochléo-récurrentiel dans le dispositif de contrôle de la phonation. *J. franç. Oto-rhino-laryng.,* **2,** 91-98 (1953).
*Egan, J. J., Psychoacoustics of the Lombard voice reflex. Doctoral dissertation, Western Reserve Univ. (1967).
*Egan, J. J., The Lombard reflex. *Arch. Otolaryng.,* **94,** 310-312 (1971).
Elliott, L. L., and Niemoeller, A. F., The role of hearing in controlling voice fundamental frequency. *Int. Audiol.,* 9, 47-52 (1970).
*Escat, E., and Rigaud, P., Les épreuves de sincérité dans les expertises otologiques. *Oto-rhino-laryng. int.,* **17,** 586-609 (1933).
Fairbanks, G. A., Systematic research in experimental phonetics, I. A theory of the speech mechanism as a servosystem. *J. Speech Hearing Dis.,* **19,** 133-139 (1954).
Fairbanks, G., Selective vocal effects of delayed auditory feedback. *J. Speech Hearing Dis.,* **20,** 333-346 (1955).
Fant, C. G. M., *Acoustic Theory of Speech Production.* The Hague: Mouton (1960).
Fargo, N., and Armacost, R. W., Bibliography: Delayed auditory feedback. *Ann. Rep. Neurocomm. Lab., Johns Hopkins Univ. Sch. Med.,* 119-134 (1968).
Fargo, N. L., Port, D. K., Mobley, R. L., and Goodman, V. E., The development of auditory feedback monitoring: IV. Delayed auditory feedback studies on the vocalizations of children between six and nineteen months. *Ann. Rep. neurocomm. Lab. Johns Hopkins Univ. Sch. Med.,* 95-118 (1968).
*Fischer, I., *Biographisches Lexikon 1880-1930.* Berlin: Urban and Schwarzenberg (1932).
Fletcher, H., *Speech and Hearing in Communication.* New York: Van Nostrand (1953).
Fletcher, H., Raff, G. M., and Parmley, F., Study of the effects of different amounts of sidetone in the telephone set. Western Electric Company Rep. No. 19412, Case No. 120622 (1918).
Fónagy, I., and Fónagy, J., Sound pressure level and duration. *Phonetica,* **15,** 14-21 (1966).
Fónagy, I., and Hermann, I., The self-regulation of loudness under usual and unusual circumstances. *Z. Phon.,* 17, 209-214 (1964).
*Fournier, J. E., Le dépistage de la simulation auditive. *Expos. ann. oto-rhino-laryng.,* 3, 107-126 (1956).
Fournier, J. E., A propos des théories du Docteur Tomatis. *Ann. Oto-laryng.,* **79,** 801-820 (1962).
*Fricke, J. E., Syllabic duration and the Lombard Effect. *Int. Audiol.,* **9,** 53-57 (1970).
Fry, D. B., Speech and language. *J. Laryng.,* **71,** 434-452 (1957).
Garde, E. J., Le réflexe cochléo-phonatoire: État actuel de la question après quelques faits expérimentaux et pathologiques. *Rev. Laryng., Bordeaux,* **86,** 631-638 (1965).
Garde, E. J., and Chevrie-Muller, C., Réponse de la voix parlée aux stimulations auditives selon leur fréquence. *Rev. Laryng., Bordeaux,* **88,** 473-481 (1967).
Gardner, M. B., Effect of noise on listening levels in conference telephony. *J. acoust. Soc. Amer.,* **36,** 2354-2362 (1964).
Gardner, M. B., Effect of noise, system gain, and assigned task on talking levels in loudspeaker communication. *J. acoust. Soc. Amer.,* **40,** 955-965 (1966).
*Gibert, P., Téléphone assourdisseur. Signe de Lombard. *Normandie méd., Rouen,* **27,** 296-301 (1911).
Goldiamond, I., Atkinson, C., and Bilger, R., Stabilization of behavior and prolonged exposure to delayed auditory feedback. *Science,* **135,** 437-438 (1962).
Goldfarb, W., and Braunstein, P., Reactions to delayed auditory feedback in schizophrenic children. In P. H. Hoch and J. Zubin (Eds.), *Psychopathology of Communication.* New York: Grune and Stratton (1958).
*Gosset, C., De quelques méthodes de dépistage de la surdité simulée. *Thès. Fac. Méd., Paris,* **171** (1942).
*Grant, D., A demonstration of cases of diseases of the throat, nose and ear. *Clin. J.,* **39,** 364-368 (1911-12).
Greenwald, A. G., Sensory feedback mechanisms in performance control: With special reference to the ideo-motor mechanism. *Psychol. Rev.,* **77,** 73-99 (1970).
Gremy, F., Chevrie-Muller, C., and Rousseau-Grenet, A. M., Effets de l'anesthésie

laryngée et de l'assourdissement sur le fonctionnement laryngeal de l'adulte normal. *Rev. Laryng., Bordeaux,* 87, 207-234 (1966).

*GROVE, W. E., Simulation of deafness. *Ann. Otol. Rhinol. Laryng.,* **52**, 573-580 (1943).

GRUBER, L., Sensory feedback and stuttering. *J. Speech Hearing Dis.,* **30**, 378-380 (1965).

*HALPHEN, E., Des lésions traumatiques de l'oreille interne. *Thès. Fac. Méd. Paris,* **22**, No. 236 (1910a).

*HALPHEN, E., De l'examen clinique de l'audition chez les accidentés. Emploi des appareils à bruit. Signe de Lombard. *Ann. Mal. Oreil. Larynx,* **37**, 97-109 (1910b).

HAM, R., and STEER, M. D., Certain effects of alterations in auditory feedback. *Folia Phoniatr.,* **19**, 53-62 (1967).

*HANLEY, C. N., and HARVEY, D. G., Quantifying the Lombard effect. *J. Speech Hearing Dis.,* **30**, 274-277 (1965).

HANLEY, C. N., and TIFFANY, W. R., Auditory malingering and psychogenic deafness. *Arch. Otolaryng.,* **60**, 197-201 (1954).

HANLEY, T. D., and STEER, M., Effect of level of distracting noise upon speaking rate, duration and intensity. *J. Speech Hearing Dis.,* **14**, 363-368 (1949).

*HARBERT, H., Functional and simulated deafness. *Naval med. Bull.,* **41**, 458-471, 716-728 (1943).

HARMS, M. A., and MALONE, J. Y., The relationship of hearing acuity to stammering. *J. Speech Hearing Dis.,* **4**, 363-370 (1939).

HARTLIEB, K., Stimm- und Sprachheilkunde aus biokybernetischer Sicht. *Folia Phoniatr.,* **19**, 368-387, 451-461 (1967).

HAYWOOD, H. C., Differential effects of delayed auditory feedback on palmar sweating, heart rate, pulse pressure. *J. Speech Hearing Res.,* **6**, 181-186 (1963).

HEBB, D. O., HEATH, E. S., and STUART, E. A., Experimental deafness. *Canad. J. Psychol.,* **8**, 152-156 (1954).

HERMANN, I., and FÓNAGY, I., Selbstregelung der Lautstärke. *Folia Phoniatr.,* **10**, 167-181 (1958).

HOLT, E. B., *Animal Drive and the Learning Process.* New York: Henry Holt (1931).

HOLZMAN, P. S., and ROUSEY, C., The voice as a percept. *J. Personal. soc. Psychol.,* **4**, 79-86 (1966).

HOLZMAN, P. S., ROUSEY, C., and SNYDER, C., On listening to one's own voice: Effects on psychophysiological responses and free associations. *J. Personal. soc. Psychol.,* **4**, 432-441 (1966).

HOOD, J. D., Bone conduction: A review of the present position with especial reference to the contributions of Dr. Georg von Békésy. *J. acoust. Soc. Amer.,* **34**, 1325-1332 (1962).

HUGGINS, A. W. F., Delayed auditory feedback and the temporal properties of the speech material. *Z. Phon.,* **21**, 53-60 (1968).

HUSSON, R., Etude stroboscopique des modifications réflexes de la vibration des cordes vocales déclenchées par des stimulations expérimentales du nerf auditif et du nerf trijumeau. *C. R. Acad. Sci. Paris,* **232**, 1247-1249 (1951).

HUSSON, R., Physiologie de la phonation et phoniatrie. *Rev. Quest. Sci., Louvain,* **15**, 75-89 (1954).

IRWIN, R. J., and MILLS, A. W., Matching loudness and vocal level: An experiment requiring no apparatus. *Brit. J. Psychol.,* **56**, 143-146 (1965).

*IWAMURA, S., An experimental study of the control of vocal intensity. *Jap. J. Otol.,* **70**, 728-744 (1967).

JAKOBSON, R., *Child Language, Aphasia and Phonological Universals.* The Hague: Mouton (1968).

*KERRISON, P. D., The tests for malingering in defective hearing. *Laryngoscope,* **28**, 662-665 (1918).

KONISHI, M., The role of auditory feedback in the control of vocalization in the white crowned sparrow. *Z. Tierpsychol.,* **22**, 770-783 (1965).

KORN, T. S., Effect of psychological feedback on conversational noise reduction in rooms. *J. acoust. Soc. Amer.,* **26**, 793-794 (1954).

KOZHEVNIKOV, V. A., and CHISTOVICH, L. A., *Speech: Articulation and Perception.* Washington, D.C.: Joint Pubs. Res. Serv., Dept. Commerce (1966).

KRYTER, K. D., Effects of ear protective devices on the intelligibility of speech in noise. *J. acoust. Soc. Amer.,* **18**, 413-417 (1946).

LADEFOGED, P., *Three Areas of Experimental Phonetics*. London: Oxford Univ., 162-165 (1967).
LAFON, J. C., *The Phonetic Test and the Measurement of Hearing*. Springfield, Ill.: Thomas 72-77 (1966).
LANE, H. L., Psychophysical parameters of vowel perception. *Psychol. Monogr.*, **76**, No. 44 (1962).
LANE, H. L., The autophonic scale of voice level for congenitally deaf subjects. *J. exp. Psychol.*, **66**, 328-331 (1963).
LANE, H. L., The motor theory of speech perception: A critical review. *Psychol. Rev.*, **72**, 275-309 (1965).
LANE, H. L., The servo-mechanism model for the acquisition and use of language. In G. Linhart (Ed.), *Proceedings of the Conference on the Psychology of Human Learning*. Prague: Acad. Sci. (1970).
LANE, H. L., CATANIA, A. C., and STEVENS, S. S., Voice level: Autophonic scale, perceived loudness and effects of sidetone. *J. acoust. Soc. Amer.*, **33**, 160-167 (1961).
LANE, H. L., and SHINKMAN, P. G., Methods and findings in an analysis of a vocal operant. *J. exp. Anal. Behav.*, **6**, 179-188 (1963).
*LANE, H. L., TRANEL, B., and SISSON, C., Regulation of voice communication by sensory dynamics. *J. acoust. Soc. Amer.*, **47**, 618-624 (1970).
LASHLEY, K. S., The problem of serial order in behavior. In L. Jeffress (Ed.), *Cerebral Mechanisms in Behavior*. New York: Wiley, 112-146 (1951).
LEE, B. S., Effects of delayed speech feedback. *J. acoust. Soc. Amer.*, **22**, 824-826 (1950).
LENNEBERG, E. H., *Biological Foundations of Language*. New York: Wiley, 96-99 (1967).
*LERMOYEZ, M., Etienne Lombard, 1869-1920. *Pr. Méd.*, **28**, 1036 (1920).
LIBERMAN, A. M., COOPER, F. S., STUDDERT-KENNEDY, M., HARRIS, K. S., and SHANKWEILER, D. P., On the efficiency of speech sounds. *Z. Phonet.*, **21**, 21-32 (1968).
LICKLIDER, J. C. R., and KRYTER, K. C., Articulation tests of standard and modified interphones conducted during flight at 5000 and 35,000 feet. Off. Sci. Res. Dvlmnt. Rep. 1976 PB 5505 (1944).
LIGHTFOOT, C., and BLACK, J. W., Rates of speaking. Reports II-III, responses to heard stimuli. Report 411-1-3, Acoustics Lab., Schl. Aviation Med. & Res., Naval Aviation Sta., Pensacola (1948).
LIGHTFOOT, C., and MORRILL, S. N., Loudness of speaking: The effect of the intensity of sidetone upon the intensity of the speaker. Joint Project Rep., No. 4, Bureau of Medicine and Surgery, U.S. Navy Proj. No. 001.053 (1949).
*LOMBARD, E., A propos de la note rectificative et de la rectification. *Ann. Mal. Oreil. Larynx*, **36**, 111-112 (1910a).
*LOMBARD, E., Note rectificative. *Ann. Mal. Oreil. Larynx*, **36**, 34-35 (1910b).
*LOMBARD, E., Le signe de l'élévation de la voix. *Ann. Mal. Oreil. Larynx*, **37**, 101-119 (1911).
*LOMBARD, E., and BALDENWECK, L., Traitement de quelques cas de mutité hystérotraumatique par le procédé de la suppression de contrôle auditif de la voix (méthode de Lombard). *Arch. méd. Pharm. mil., Paris*, **66**, 501-503 (1916-17).
LOTZMAN, G., Zur Anwendung variierter Verzögerungszeiten bei Balbuties. *Folia Phoniatr.*, **13**, 276-312 (1961).
*MACKENZIE, G. W., Simulated unilateral deafness. *Laryngoscope*, **39**, 103-108 (1929).
MACNEILAGE, P., Motor control of serial ordering of speech. *Psychol. Rev.*, **77**, 182-196 (1970).
MACNEILAGE, P., ROOTES, T. P., and CHASE, R., Speech production and perception in a patient with severe impairment of somesthetic perception and motor control. *J. Speech Hearing Res.*, **10**, 449-467 (1967).
*MAFFEO, L., Alcuni metodi pratici per scoprire la simulazione della sordità. *Morgagni*, **76**, 1151-1156 (1934).
MARAIST, J., and HUTTON, C., Effects of auditory masking upon the speech of stutterers. *J. Speech Hearing Dis.*, **22**, 385-389 (1957).
*MATSUZAKI, T., and IWAMURA, S., The relation between hearing and phonation. *Perspectives in Otology (Jibitenbo)*, **8**, 93-98 (1965).
MCCROSKEY, R. L., JR., The relative contribution of auditory and tactile cues to certain aspects of speech. *Sth. Speech J.*, **24**, 84-90 (1958).

McKown, F. W., and Emling, J. W. A., System of effective transmission data for rating telephone cricuits. *Bell Syst. tech. J.*, **12**, 331-346 (1933).

Mead, G. H., *Mind, Self and Society*. Chicago: Univ. of Chicago. (1934).

Molinari, G. A., and Pivotti, G. S., The cochleorecurrential reflex. *Arch. Otolaryng.*, **77**, 92-100 (1963).

*Montagne, P., Contribution à l'étude de la valeur des épreuves de Lombart [sic] et de l'acoumétrie réciproque. *Thès. Fac. Méd. Paris*, No. 942 (1951).

Morgon, A., Lafon, J. C., and Prelot, J. P., Le contrôle audiophonatoire. *Folia Phoniatr.*, **16**, 193-200 (1964).

*Moulonguet, A., *Manuel d'Expertise en Otologie*. Paris: Masson (1933).

Mowrer, O. H., *Learning Theory and Personality Dynamics*. New York: Ronald Press (1950).

Mysak, E. D., A servo model for speech therapy. *J. Speech Hearing Dis.*, **24**, 144-149 (1959).

Mysak, E. D., Servo theory and stuttering. *J. Speech Hearing Dis.*, **25**, 188-195 (1960).

Nessel, E., Die verzögerte Sprachrückkopplung (Lee-Effekt) bei Stotterern. *Folia Phoniatr.*, **10**, 199-204 (1958).

*Newby, H. A., *Audiology*. New York: Appleton, 156-157 (1958).

Noll, A. M., Effects of head and air-leakage sidetone during monaural telephone speaking. *J. acoust. Soc. Amer.*, **36**, 598-599 (1964a).

Noll, A. M., Subjective effects of sidetone during telephone conversation. *IEEE Trans. Comm. Electron.*, **83**, 228-231 (1964b).

Nottebohm, F., The role of sensory feedback in the development of avian vocalizations. Doctoral dissertation, Univ. Calif., Berkeley (1966).

*Panconcelli-Calzia, G., Die Bedingtheit des Lombardschen Versuches in der Stimm- und Sprachheilkunde. *Acta otolaryng.*, **45**, 244-251 (1955).

*Panconcelli-Calzia, G., Der Wert des Lombardschen Versuches auf Laryngktomierte. *Acta otolaryng.*, **49**, 162-164 (1958).

Penn, J., Voice and speech patterns of the hard of hearing. *Acta otolaryng. Suppl.*, 124 (1955).

Peters, R. W., The effect of changes in sidetone delay and level upon rate of oral reading of normal speakers. *J. Speech Hearing Dis.*, **19**, 483-490 (1954).

Peters, R. W., The effect of filtering of sidetone upon speaker intelligibility. *J. Speech Hearing Dis.*, **20**, 371-375 (1955).

Peters, R. W., Effect of acoustic environment upon speaker intelligibility. *J. Speech Hearing Dis.*, **21**, 88-93 (1956).

Piaget, J., *La naissance de l'intelligence chez l'enfant*. Paris: Delachoux and Niestlé (1948).

Pickett, J. M., Effects of vocal force on the intelligibility of speech sounds. *J. acoust. Soc. Amer.*, **28**, 902-905 (1956).

Pickett, J. M., Limits of direct speech communication in noise. *J. acoust. Soc. Amer.*, **30**, 278-281 (1958).

*Pitman, L. K., A device for detecting simulated unilateral deafness. *J. Amer. med. Ass.*, **121**, 752-753 (1943).

*Portmann, M., and Portmann, C., Le dépistage audiométrique de la simulation auditive. *Arch. Mal. prof.*, **14**, 25-31 (1953).

*Priest, R. E., Tests for unilateral deafness. *Arch. Otolaryng.*, **42**, 138-143 (1945).

Radley, W. G., Speech communication under conditions of deafness or loud noise. *J. Instn. elect. Engrs.*, **95**, 201-216, 544-550 (1948).

Reynolds, G. S., and Stevens, S. S., Binaural summation of loudness. *J. acoust. Soc. Amer.*, **32**, 1337-1344 (1960).

Ringel, R. L., and Steer, M. D., Some effects of tactile and auditory alterations on speech output. *J. Speech Hearing Res.*, **6**, 369-378 (1963).

Rousey, C., and Holzman, P. S., Some effects of listening to one's own voice systematically distorted. *Percep. mot. Skills*, **27**, 1303-1313 (1968).

*Rubenovitch, P., and Pastier, J., L'épreuve de Lombard appliquées en psychiatrie (contributions à l'étude des réflexes conditionnels). *Ann. Med. Psychol.*, **96**, 116-121 (1938).

*Ruppmann, E., and Tegtmeier, W., Zur quantitativen Messung des Lombardschen Versuches. *Z. Laryng. Rhinol. Otol.*, **40**, 791-796 (1961).

*Russel, R. D., Detection of simulated deafness. *Laryngoscope*, **44**, 201-210 (1934).

Rutherford, D., Auditory motor learning and the acquisition of speech. *Amer. J. phys. Med.*, **46**, 245-251 (1967).

*Scal, J. C., Malingering deafness: Tests in its detection and report of two cases. *Arch. Otolaryng.*, 3, 237-241 (1926).

Schliesser, H. F., and Coleman, R. O., Effectiveness of certain procedures for alteration of auditory and oral tactile sensation for speech. *Percept. mot. Skills*, **26**, 275-281 (1968).

*Sebileau, P., Le diagnostic de la surdité simulée. *Ann. Mal. Oreil. Larynx*, **37**, 193-195 (1911).

Sedlacek, K., Les relations de la parole et de l'audition. In J. Tarneaud (Ed.), *La voix et la parole*. Paris: Maloine, 67-80 (1950).

Shearer, W. M., Cybernetics in the treatment of voice disorders. *J. Speech Hearing Dis.*, **24**, 280-282 (1959).

Singh, S., Brokaw, S. P., and Black, J. W., Effects of delayed sidetone, noise and syntactic structure on the level and duration of speech. *J. verb. Learn. verb. Behav.*, **6**, 629-633 (1967).

Smith, S., and Guthrie, E. R., *General Psychology*. New York: Appleton (1923).

Spilka, B., Relationships between certain aspects of personality and some vocal effects of delayed speech feedback. *J. Speech Dis.*, **19**, 491-503 (1954).

Stevens, S. S., The measurement of loudness. *J. acoust. Soc. Amer.*, **27**, 815-829 (1955).

Stevens, J. C., Mack, J. D., and Stevens, S. S., Growth of sensations on seven continua as measured by force of handgrip. *J. exp. Psychol.*, **59**, 60-67 (1960).

Stromsta, C., Experimental blockage of phonation by distorted sidetone. *J. Speech Hearing Res.*, **2**, 286-301 (1959).

Stromsta, C., Delays associated with certain sidetone pathways. *J. acoust. Soc. Amer.*, **34**, 392-396 (1962).

Studdert-Kennedy, M., Liberman, A. M., Harris, K. S., and Cooper, F. S., Motor theory of speech perception: A reply to Lane's critical review. *Psychol. Rev.*, **77**, 234-249 (1970).

*Sullivan, R. F., Report on Dr. Lombard's original research on the voice reflex test for malingering. (Trans. of M. Weiss, "Sur un travail du Dr. Lombard, intitulé: Contributions à la séméiologie de la surdité. Un nouveau signe pour en dévoiler la simulation.") *Acta otolaryng.*, **56**, 490-492 (1963).

*Takakura, M., Concerning the influence of noise on phonation. *Jap. J. Otol.*, **60**, 129 (1957).

*Tarneaud, J., *Traité pratique de phonologie et de phoniatrie*. Paris: Maloine (1941).

*von Tato, Objektive audiometrie. *Arch. Ohr-usw. Heilk. u. Z. Hals-usw., Heilk.*, **164**, 477-486 (1954).

*Taylor, G. J., An experimental study of tests for the detection of auditory malingering. *J. Speech Hearing Dis.*, **14**, 119-130 (1949).

*Thomas, A., Le dépistage de la simulation de la surdité. *Thès. Fac. Méd. Paris*, No. 144 (1961).

Tiffany, W. R., and Hanley, C. N., Delayed speech feedback as a test for auditory malingering. *Science*, **115**, 59-60 (1952).

Tomatis, A., Recherches sur la pathogénie du bégaiement. *J. franc. Oto-rhino-laryng.*, **3**, 384-391 (1954).

Tomatis, A., Relations entre l'audition et la phonation. *Ann. Télécomm.*, **2**, 3-8 (1956).

Tomatis, A., Conditionnement audio-vocal. *Bull. Acad. nat. Méd.*, **144**, 197-200 (1960).

Van Michel, C., and Le Maire, G., Le comportement de la voix humaine lors d'une stimulation auditive biauriculaire. *C. R. Soc. Biol.*, **160**, 433-436 (1965).

Van Michel, C., and Le Maire, G., Influence d'une stimulation auditive biauriculaire sur l'émission de la voix humaine. *Acta Oto-rhino-laryng. belg.*, **21**, 66-71 (1967).

Vannier, J., Saumont, R., Labarraque, L., and Husson, R., Production expérimentale de blocages synaptiques récurrentiels par des stimulations auditives homorythmiques avec déphasages réglables. *Rev. Laryng. Suppl., Bordeaux*, 160-168 (1954).

*Waldron, D. L., The Lombard voice reflex test: An experimental study. Doctoral dissertation, Stanford Univ. (1960).

*Weber, H. C., Simulated deafness. *U.S. Naval med. Bull.*, **29**, 209-220 (1931).

Webster, J. C., and Klumpp, R. G., Effects of ambient noise and nearby talkers on a face-to-face communication task. *J. acoust. Soc. Amer.*, **34**, 936-941 (1962).

WEBSTER, R. L., and LUBKER, B. B., Interrelationships among fluency producing variables in stuttered speech. *J. Speech Hearing Res.*, **11**, 754-766 (1968).

WEBSTER, R. L., SCHUMACHER, S. J., and LUBKER, B. B., Changes in stuttering frequency as a function of various intervals of delayed auditory feedback. *J. abnorm. Psychol.*, **75**, 45-49 (1970).

*WEISS, M., Sur un travail du Dr. Lombard, intitulé: Contribution à la séméiologie de la surdité. Un nouveau signe pour en dévoiler la simulation. *Bull. Acad. Méd.*, **64**, 127-130 (1910).

*WETTERWALD, J., La simulation de la surdité: Méthodes actuelles de dépistage. *Thès. Fac. Méd. Paris*, No. 1008 (1955).

*YANNOULIS, G., Der Lombardsche Versuch in db und Hz gemessen. *Folia Phoniatr.*, **15**, 312-313 (1963).

YATES, A. J., Delayed auditory feedback. *Psychol. Bull.*, **60**, 213-232 (1963).

YATES, A. J., Delayed auditory feedback and shadowing. *Quart. J. exp. Psychol.*, **17**, 125-131 (1965).

YENI-KOMSHIAN, G., CHASE, P. A., and MOBLEY, R. L., The development of auditory feedback monitoring: II. Delayed auditory feedback studies on the speech of children between two and three years of age. *J. Speech Hearing Res.*, **11**, 307-315 (1968).

ZALOSH, S., and SALZMAN, L. P., Aftereffects of delayed auditory feedback. *Percept. mot. Skills*, **20**, 817-823 (1965).

ZERNERI, L., Tentatives d'application de la voix retardée ("Delayed speech feedback") dans la thérapie du bégaiement. *J. franc. Oto-rhino-laryng.*, **15**, 415-418 (1966).

Received September 7, 1971.