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The Perception of Speech Sounds by Deafened Persons

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In a previous paper by Fletcher and Galt [J. Acoust. Soc. Am. 22, 89 (1950)] a method was described for measuring experimentally and also for calculating the interpretation aspect of the perception of speech. The listeners were considered to have normal hearing. In the present paper the same principles are applied to persons having abnormal hearing.

IT is well known that there are three types of hearing loss that must be distinguished, namely, (1) conductive deafness, (2) nerve deafness, and (3) mixed deafness. The first type is due to some trouble that blocks the acoustical transmission path between the air sound waves and the nerve endings on the basilar membrane. The second type is due to trouble with the nerve endings or the nerves of the auditory nerve. The third type occurs when both these causes are present.

As is well known, the hearing loss is represented by an audiogram whose ordinates are expressed in db from a reference level. This reference level is supposed to correspond to the average pressure level at which pure tones are just perceived by normal ears. The value of the hearing loss at the frequency f will be designated β_c for conductive deafness, β_n for nerve deafness, and β_m for mixed deafness.

When a person has a conductive deafness of β_c and at the same time a nerve deafness β_n, then

$$\beta_m=\beta_c+\beta_n. \quad (1)$$

The air conduction audiogram gives directly the values of β_m, and the bone conduction audiogram gives the values of β_n. If the conductive deafness is made artificially by putting an object in the external ear canal (such as a finger, cotton or wax), then it is obvious that the hearing loss β_c can be treated as though there were interposed between the talker and the listener a transmission system having a response R where $R=-\beta_c$. Thus for this case the value β_c can be subtracted from the response of the system being used by the talker-listener pair. In other words, β_c may be considered as an additional attenuation in the transmission system and then the procedure for calculation is the same as for the normal ear.

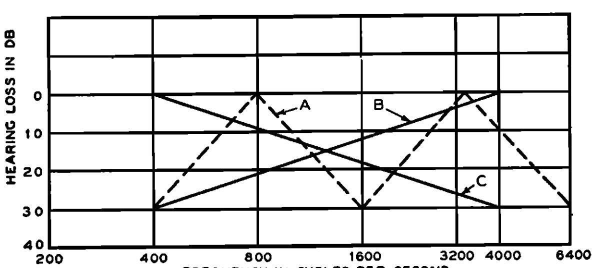

FIG. 1.

If this same philosophy is applied to all conductive deafness, then it would follow that a person having a hearing loss β_c would obtain the highest articulation score by using a system having a response R equal to the hearing loss β_c or such that $R-\beta_c$ would be the same for different frequencies.

On the other hand, a person with a small amount of deafness and an audiogram which is not flat uses this hearing characteristic daily to hear speech which is transmitted by an essentially flat response system, the air path between the speaker and the listener. So when a transmission system departs from a flat response the received speech, to such a listener, appears somewhat distorted and therefore one might expect that, under such conditions, a lower articulation score would result.

Since these two points of view lead to different calculated results, one asks the question, "Which one agrees with the observed facts?" Unfortunately, there are no data* that are sufficiently accurate to distinguish between these two points of view when the hearing losses are moderate. One would expect such a result because the difference in the calculated results using these two points of view is very small indeed, as will now be illustrated.

Consider the three audiograms A, B, and C in Fig. 1, when no hearing loss is greater than 30 db. Under the first point of view if such a person uses a flat response system, the calculated articulation index values are 0.95, 0.96, and 0.95, respectively. The corresponding syllable articulation values are 0.968, 0.970, and 0.968, respectively. Using the second point of view, the articulation index is unity, which corresponds to 0.976 for the three types. The difference between 0.970 and 0.976 is less than the experimental error even when a very elaborate technique is used in making the articulation tests. If the *PB* lists developed at Harvard University and used for articulation testing with deafened persons are used, the difference between the two points of view is even smaller. So there seems to be no hope of determining for such moderate hearing losses which point of view is correct. Either point of view shows the foolishness of trying to make the response of a hearing aid so it will fit the audiogram when the latter does not depart

* The book, *Hearing Aids: An Experimental Study of Design Objectives*, by Hallowell Davis and his associates contains the most comprehensive set of data yet obtained and frequent reference to it as *Hearing Aids* will be made.

from flat by more than 30 db, in so far as the intelligibility of speech is concerned. However, for large departures from a flat audiogram, it is my opinion based upon a limited experience that the first point of view is more nearly correct.

The nerve deafness β_n is considered to have the same effect upon articulation scores as though the ear were normal but a listening end noise were present which produces a masking M which is equal to β_n.

When no external noise is present then the procedure for calculating the articulation index A is the same as outlined in the paper cited above except the response $R-\beta_c$ is used in place of R and $R-\beta_n$ is used in place of $R-M$, where M is the masking.

When an external noise is present in the ear canal then if its level is high enough it will cause additional masking to that produced by β_n which may be calculated as follows: Let the noise be specified in terms of the pressure level β, in the ear canal, of pure tones which can just be perceived by a normal ear in the presence of the noise. This is called the masking pressure level of the noise. When white noise is used this is equivalent to specifying the pressure level of the noise in critical frequency band widths. The pressure level in a critical frequency band width of a fictitious noise in the ear canal which will account for the nerve deafness then must be

$$\beta_n+\beta_c+\beta_0=\beta_m+\beta_0,$$

where β_0 is the pressure level under the ear cap of the audiometer receiver which is used to determine β_c and β_n when the dial of the audiometer is set at zero hearing loss. Therefore, if β_m' is the effective mixed deafness due both to the actual deafness and also that caused by the presence of the noise, then

$$\beta_m'+\beta_0=10\log[10^{\beta/10}+10^{(\beta_m+\beta_0)/10}]. \quad (2)$$

This value of β_m' can be used in place of β_m and the precedure then is as outlined above for the no noise condition.

When the masking level β resulting from the noise is 10 db less then $\beta_m+\beta_0$ it produces no change in the effective mixed deafness, that is, $\beta_m'=\beta_m$. When the usual type of audiometer is used (Bureau of Standards calibration by means of a coupler) then the values of β_0 are as follows for the six frequencies used in audiometry:

Table I.

$f=250$	500	1000	2000	4000	8000
$\beta_0=40$	25	17	17	15	21

Recent measurements at the Bureau of Standards† show that measurements of the pressure level under an ear cap on the ear gives values approximately the same as those in Table I except for the frequency 250 cps. For this frequency the pressure level β_0 was about 4 db lower than that found on the coupler, but depended upon the pressure used in holding the receiver on the ear.

Calculations by the above method are long, particularly when sending end noise is present. Even so, one would be justified in making exact calculations if any experimental data were available comparable in accuracy to those given in the previous paper for normal ears. A comparison of calculated and observed results would then show whether or not the assumptions on which the method depends are justified for deafened listeners. Because of the great difficulty in obtaining such data for deafened ears there is necessarily a very large experimental error.

For these reasons, the method of calculating the articulating index has been very much simplified by making approximations which will now be described. This simplified method is not only useful for deafened listeners but can be applied to all cases where there are no abrupt changes in the response curves.

The first simplification is to use only the six frequencies used in audiometry, namely, 250, 500, 1000, 2000, 4000, and 8000 cps. The responses of the hearing aid or the telephone system, and the hearing losses β_c and β_n, are given for these six frequencies.

The articulation index A is obtained as the product of four factors—namely, the frequency distortion factor F, the volume factor V, the ear distortion factor E, and the proficiency factor p or

$$A=F.V.E.p. \quad (3)$$

The factor F depends upon the relative response at different frequencies. The factor V depends upon the level of the speech sounds above the threshold level. The factor E depends upon the nearness of the level of speech to the feeling or hurting level. The proficiency factor p depends upon the proficiency of the listener in recognizing speech sounds made by the talker. The procedure when no external noise is present will first be outlined. For the philosophy back of this procedure, the reader is referred to the paper already cited.

The factor F is composed of two terms or

$$F=2/3F_c+1/3F_m, \quad (4)$$

where

$$F_c=\sum_1^6 D_kW_k, \quad (5)$$

and where W_k is obtained from the response of $R-\beta_c$ and

$$F_m=\sum_1^6 D_kW_k', \quad (6)$$

where W_k' is obtained from the response $R-\beta_m$. The six values of D_k are as follows:

$f_k=250$	500	1000	2000	4000	8000
$D_k=0.04$	0.13	0.23	0.30	0.25	0.05

These values are obtained from the frequency-importance curve D given in the paper already cited, and

† Am. Standards Spec. Z-245–1951.

TABLE II.

(1) Values of $W(\chi)$ vs χ

x	0	1	2	3	4	5	6	7	8	9	Difference
0	1.0	0.997	0.994	0.990	0.985	0.980	0.973	0.966	0.958	0.950	0.007
10	0.940	0.930	0.920	0.910	0.899	0.887	0.874	0.860	0.846	0.832	0.012
20	0.818	0.804	0.789	0.774	0.759	0.744	0.728	0.712	0.695	0.678	0.017
30	0.660	0.642	0.623	0.603	0.582	0.561	0.539	0.516	0.492	0.467	0.022
40	0.441	0.415	0.390	0.365	0.340	0.315	0.291	0.267	0.244	0.222	0.022
50	0.202	0.183	0.165	0.148	0.132	0.118	0.104	0.091	0.080	0.070	0.013
60	0.060	0.050	0.040	0.030	0.022	0.015	0.010	0.005	0.000		0.010

were obtained from the equation

$$D_k=\int_{.7f_k}^{1.4f_k} D.df, \tag{7}$$

where f_k is successively the values of f_k shown above. The values of W_k or W_k' depend upon χ_w or χ_w', the number of db the response for the frequency band is below a weighted average response which will now be specified.

Examine the three values of $R-\beta_c$ for $k=2$, 3, and 4 or for frequencies of 500, 1000, and 2000 cps. The average of the two highest values is designated $(\langle R-\beta_c\rangle)_2$ and the average of the three values is designated $(\langle R-\beta_c\rangle)_3$. These values correspond approximately to $\bar{R}_1$ and $\bar{R}_4$ of the previous paper. The weighted average response $\langle R-\beta_c\rangle$ is taken as the average of these two values or

$$\langle R-\beta_c\rangle=\tfrac{1}{2}(\langle R-\beta_c\rangle)_2+\tfrac{1}{2}(\langle R-\beta_c\rangle)_3. \tag{8}$$

Then the value χ_w is given by

$$\chi_w=\langle R-\beta_c\rangle-(\langle R-\beta_c\rangle). \tag{9}$$

Similarly

$$\chi_w'=\langle R-\beta_m\rangle-(R-\beta_m). \tag{10}$$

Thus, the six values of χ_w and χ_w' are obtained. The corresponding values of W are obtained from Table II. When χ_w is negative, the value of W is unity. This then completes the method of calculating F.

The factor V depends upon a quantity χ_v which for most systems is approximately the db above the threshold level for hearing the speech. It is given by

$$\chi_v=\alpha-\alpha_0-\phi\Delta\alpha. \tag{11}$$

The quantity $\Delta\alpha$ is given by

$$\Delta\alpha=(\langle R-\beta_m\rangle)_2-(\langle R-\beta_m\rangle)_3. \tag{12}$$

The quantity α is the amplication in db or gain in the system from some reference level, and α_0 is the corresponding gain to bring the speech at the listeners ear to the threshold level.

TABLE III. Values of ϕ *versus* χ_v.

$\chi_v=0$	5	10	15	20	25	30	40	110
$\phi=0$	0.22	0.45	0.65	0.85	0.93	0.97	1.0	1.0

The factor ϕ depends upon χ_v as shown in Table III. The threshold gain α_0 is computed from the equation

$$\alpha_0=-\beta_t-(\langle R-\beta_m\rangle)_2+12, \tag{13}$$

where β_t is equal to the talking level of the speaker at one meter distance from the lips. For conversational speech this is usually between 65 and 70 db. The response R is the orthotelephonic response for the system, and is the gain at each frequency with reference to a system where the speaker talks directly through the air to listener whose ears are one meter away from the lips of the speaker.

The relation between χ_v and V is given in Table IV. This completes the process of finding the factor V for each gain α.

The factor E is dependent upon χ_E which is the db difference between the maximum gain α_t which can be tolerated and the actual gain α in the system or

$$\chi_E=\alpha_t-\alpha. \tag{14}$$

It was found that the maximum level of speech that could be tolerated by a group of listeners, whose average hearing loss was -4 db, was 110 db above their threshold level. Since their threshold intensity level for speech was found to be 8 db, the tolerable intensity level for speech is 118 db. Tests by Davis indicated this level was about the same for deafened ears varying only ± 10 db from the tenderest to the toughest ear. Therefore,

$$\alpha_t+\beta_t+\bar{R}_2=118\pm 10, \tag{15}$$

where β_t is the speech level at the listeners ear and $\bar{R}_2$, the average of the two highest response values of the system at the three frequencies 500, 1000, and 2000 cps.

The value of χ_E then becomes

$$\chi_E=118\pm 10-\beta_t-\bar{R}_2-\alpha. \tag{16}$$

The relation between χ_E and E is given in Table V. When X_E exceeds 40 db the value of E is always unity. Since no tolerable levels were determined for each individual case, the value of 118 was taken for all cases.

The proficiency factor p is dependent upon the ability of the listener to recognize speech sounds spoken by the speaker and transmitted to the listener by an ideal system. If one hears speech every day and has had some practice writing speech sounds, then the factor p approaches unity. If the listener does not understand very well the language being spoken or is very hard of hearing so that speech sounds are heard only occasionally, then this factor may be as low as 0.5. For the articulation data given in *Hearing Aids* the factor p was taken to give the best fit for the flat system. It will be seen that the values obtained in this way are reasonable ones.

These data will be used to illustrate the method of calculation and for drawing some general conclusions regarding hearing aids.

Six different systems were used in these tests which are designated Flat, HP-6, HP-12, LP-6, and LP-12. The orthotelephonic responses for the six frequencies mentioned above are given in Table VI. These were obtained from the response curves given in *Hearing Aids* when $\alpha=0$, which corresponds to an attenuator setting of 10 db. The values of $\bar{R}_2$ and α_c calculated from 14 are given in the last two columns.

It will be remembered that the orthotelephonic reference for $R=0$ is the air path between a talker and a listener in a free acoustic field with the talker at one meter distance from a line joining the two ears of the listener, who faces the talker. So corrections to the response curves given in *Hearing Aids* must be made to

TABLE IV. Values of V *versus* χ_v.

χ_v	0	1	2	3	4	5	6	7	8	9
0	0	0.01	0.02	0.03	0.04	0.05	0.06	0.07	0.09	0.10
10	0.11	0.13	0.14	0.16	0.18	0.20	0.22	0.24	0.26	0.28
20	0.30	0.32	0.34	0.36	0.38	0.41	0.43	0.45	0.48	0.51
30	0.54	0.57	0.60	0.62	0.64	0.66	0.68	0.70	0.72	0.74
40	0.75	0.77	0.79	0.80	0.81	0.83	0.85	0.86	0.87	0.88
50	0.89	0.90	0.91	0.92	0.93	0.94	0.95	0.96	0.97	0.98
60	0.98	0.99	0.99	0.99	1.0	1.0	1.0	1.0	1.0	1.0

give orthotelephonic responses which are the ones for which the method applies for calculating articulation scores outlined here. The talking levels β_t were maintained at 66 db at one-meter distance which corresponds to 70 db at the distance of 25 inches used in their data. When the 250–7000 cps filter is introduced 4 db must be subtracted from the value of R at 250 cps.

The observed articulation scores were obtained by by these investigators when these six systems were used with listeners having various kinds and amounts of hearing loss. The P_M lists were generally used and only those cases using them will be considered here.

Two types of audiogram were given in this report, one taken at the psycho-acoustic laboratory and one taken at the M. E. E. I. hospital in Boston. The former are considered more accurate and will be used in the calculation. These hearing losses were given in terms of the pressure levels above the Sivian and White pressure levels for the threshold of hearing. Sivian and White values for the six frequencies are given in Table VII. If these are compared to the standard pressure threshold levels given in Table I it will be seen that the correction given in the third line must be subtracted from the Harvard observed hearing losses to get those corre-

TABLE V. Relation between X_E and E.

$\chi_E=0$	10	20	30	40	50
$E=0.83$	0.87	0.93	0.98	1.0	1.0

sponding to values obtained by the standard audiometer. When this correction is made the resulting values of hearing loss obtained compare favorably with those obtained by the audiometer in the M. E. E. I. hospital.

The three listeners described as young men having normal hearing did not have tests with a standard audiometer but obtained approximately the same threshold pressure levels as given by the Sivian-White threshold curve. They were also practiced observers so for the reasons given in the previous paper already cited, the hearing loss for them for speech was taken as -4 db. This differs from that obtained from Table VII which would be -10.5 db. The difference 5.5 db is considered practice effect.

Articulation results with these listeners using the three systems, Flat, HP-6, and LP-6, and with quiet; and two noise conditions are given in Fig. 2. The solid lines are calculated by the short method outlined above. These calculations indicate that for gains less than 30 db above the threshold gain the noise does not affect the articulation. However, the observed data indicate that in this range the articulation is higher when the noise is present. This must be the effect of the noise upon the speakers rather than upon the listeners. When the noise is turned on, the speaker is immersed in it and will inevitably raise the intensity of the consonant sounds, even though the monitoring meter shows a constant talking level. It is suggested that this is the effect shown in these data.

Before these calculations could be made, a relation between the articulation index A and the articulation S_w, obtained with the *PB* lists, must be obtained. By using the short method, calculations were made of the articulation index A *versus* α for the three systems (quiet) shown in Fig. 2. Values of S_w were chosen to give the best fit for the data shown by the top three curves of Fig. 2.

The values of A *vs* S_w which were chosen are given in Table VIII.

With the various approximations which have been described it is estimated that results can be obtained by the short method which are not in error by more than the observational error, and the calculations are comparatively simple.

TABLE VI.

System	$f=250$	500	1000	2000	4000	8000	$\bar{R}_2$	α_t
Flat	$R=58$	62	59	53	47	46	60	−8
HP-6	$R=30$	40	42	42	41	43	42	10
HP-12	$R=9$	23	32	38	40	43	35	17
LP-6	$R=52$	52	43	30	19	12	47	5
LP-12	$R=51$	48	34	16	0	−14	41	11

TABLE VII.

f = 250	500	1000	2000	4000	8000
β_0 (S & W) = 26	14	7	5	8	19
correction = 10	11	10	12	7	2

Chart I enables one to follow the simplified calculations when no external noise is present. In lines 1, 2, and 3 the values of k, f_k, and D_k are given. They are the same for all systems and listeners and callers. In line 4 the values of β_M are taken directly from the air conduction audiogram. In this illustration the values are taken for the case FB-L given in *Hearing Aids*. The calculation is for the Flat system. In line 5 the values β_n are taken directly from the bone conduction tests. The values of the conductive deafness β_c is the difference between β_m and β_n and are given in line 6. The values of R are given in line 7, from Table VII. These data, together with a knowledge of the proficiency factor p, which in this case is taken as 1.1, enables one to make the calculation. In Sec. (2) of the chart the steps for calculating F_C are shown in Sec. (3). The values of F, α_0, and $\Delta\alpha$, are tabulated in Sec. (4). In the fifth section corresponding values of α and S_w are calculated as indicated. The value of A is calculated by (3) and the corresponding S_W is obtained from Table VIII.

When noise is present the value of β_m', calculated from 2, is substituted for β_m in the above calculations, and the procedure is then the same as shown in Chart I provided the noise is independent of the gain α.

In the Harvard tests, however, the noise level and also the speech level were held constant at the mouth of the transmitting microphone. Consequently, not only the speech level but also the noise level received by the listeners changed as the gain α changed. It also was different for the different systems. The noise was not steady but full of static crashes. It can therefore be best specified at the listeners ear in terms of the masking level β of pure tones which can just be perceived in its presence.

Such levels for the Flat system and for the condition when $\alpha = -37$ db, and for the noise condition specified by $S/10$, are given in second row of Table IX for the six frequencies. The values are the average levels from 0.7 to 1.4 f as obtained from Fig. 56 of *Hearing Aids*.‡ In the last row the values of β when $\alpha = 0$ are given.

Since the masking level β results from the noise for a normal ear, then when any system is used with a gain α is

$$\beta = \beta(0) + \alpha - \Delta R, \qquad (17)$$

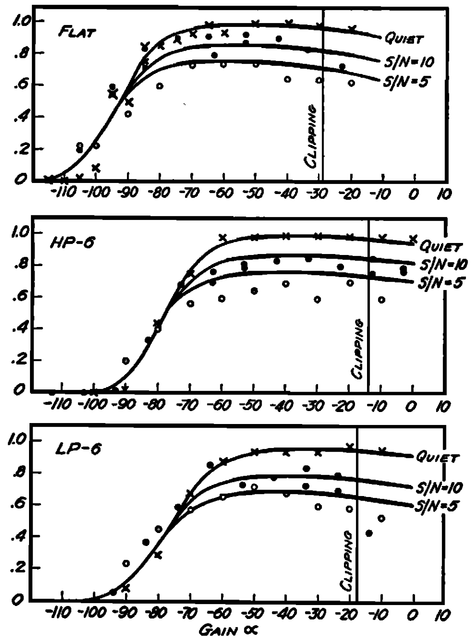

FIG. 2.

where ΔR is the difference in response between the Flat system and that of any of the other five systems. The values of ΔR for each system is obtained from the published response curves. So the values of $\beta - \alpha$ for each system can be calculated and are given in Table X.

It is thus seen that the received spectrum level curves for the sending end noise were greatly changed as one switched from one system to the other. These values are all for the noise condition indicated by $S/N = 10$. For the condition $S/N = 5$, then 5 db must be added to these values and for the condition indicated by $S/N = 15$, then 5 db must be subtracted from these values.

So it is seen that β_m' will be different for each gain setting α. So one proceeds as follows. A gain α is chosen and the corresponding values of β_m' is computed from 2. Using this value in place of β_m the values of α_0, $\phi\Delta\alpha$, and χ_v are calculated. From this the value V is obtained. The values of E and F_C are the same as for the no noise condition. The values of the last row of Chart I were calculated in this way.

The observed data in *Hearing Aids* are plotted with abscissas as db above the clipping level, which was observed on an oscilloscope as the level where the clipping of the peaks started. This level was set so that the levels of speech received by the listener would not be intolerable. The relation between this abscissa and the gain α

TABLE VIII.

$A = 0$	0.1	0.15	0.20	0.25	0.30	0.35	0.40	0.45	0.50	0.60	0.70	0.80	0.90	1.00
$S_w = 0$	0.08	0.15	0.24	0.32	0.42	0.51	0.59	0.67	0.74	0.84	0.90	0.95	0.98	0.995

‡ NOTE. The values of β (−37) given in this figure are 40 db too low as established after the book was published. So 40 db is added to each ordinate in this curve except for 8000 cycles. Here it was found that only 34 db needed to be added.

CHART I. Simplified method of calculating articulation index.

(1)	$k=$	1	2	3	4	5	6	Date—May 15, 1952
	$f_k=$	250	500	1000	2000	4000	8000	Listener—FB-L
	$D_k=$	0.04	0.13	0.23	0.30	0.25	0.05	Caller—9EP
	$\beta_m=$	42	50	63	58	75	98	$\beta_t=66$, $p=1.1$
	$\beta_n=$	30	35	45	50	65	88	System—Flat, $\alpha_t=-8$
	$\beta_c=$	12	15	18	8	10	10	$CL=124$
	$R=$	54	62	59	53	47	46	Noise $S/N=10$
(2)	$R-\beta_m=$	12	12	−4	−5	−28	−52	$(\langle R-\beta_m\rangle)_2=4$
	$\langle R-\beta_m\rangle-(R-\beta_m)=$	···	···	1	2	25	49	$(\langle R-\beta_m\rangle)_3=1$
	$W=$	1.0	1.0	1.0	0.99	0.74	0.22	$\langle R-\beta_m\rangle=\frac{1}{2}(\langle R-\beta_m\rangle)_2+\frac{1}{2}\langle R-\beta_m\rangle_3=3$
	$W.D=$	0.04	0.13	0.23	0.30	0.18	0.01	$\Sigma W.D=F_m=0.89$
(3)	$R-\beta_c=$	42	47	41	45	37	36	$(\langle R-\beta_c\rangle)_2=46$
	$\langle R-\beta_c\rangle-(R-\beta_c)=$	3	···	4	···	8	9	$(\langle R-\beta_c\rangle)_3=44$
	$W=$	0.99	1.0	0.98	1.0	0.96	0.95	$\langle R-\beta_c\rangle=45$
	$W.D=$	0.04	0.13	0.225	0.30	0.240	0.047	$\Sigma W.D=F_c=98$

$$F=\tfrac{2}{3}F_c+\tfrac{1}{3}F_m=0.95$$
$$\alpha_0=-\beta_t+12-(R-\beta_m)_2=-58 \quad \Delta\alpha=(R-\beta_m)_2-(R-\beta_m)_3=$$
$$\chi_v=\alpha-\alpha_0-\phi\Delta\alpha \quad \text{and} \quad \chi_E=\alpha_t-\alpha=-8-\alpha$$

(5)	$X_v=$	0	10	20	30	40	47	60	70	80	90
	$V=$	0	0.11	0.30	0.54	0.75	0.86	0.98	1.0	1.0	1.0
	$\phi=$	0	0.45	0.85	0.98	1.0	1.0	1.0	1.0	1.0	1.0
	$\phi\Delta\alpha=$	0	2	3	3	3	3				
	$\alpha=$	−58	−46	−35	−25	−15	−8				
	$\chi_E=$		38	27	17	7	0				
	$E=$		1.0	0.97	0.91	0.86	0.83				
	$Ap=$	0	0.12	0.30	0.51	0.67	0.74				
	$S_w=$	0	0.10	0.42	0.75	0.88	0.92				
	S_w (with noise)=			0.37	0.71	0.81	0.81				

for the system can be deduced as follows: The response curves given above are for $\alpha=0$ and correspond to a setting on the attenuation box of 10 db.

Then the gain α_c corresponding to the clipping level CL is related to observed reading on the attenuation box CA when clipping occurred by

$$-\alpha_c=CA-10. \tag{18}$$

From this equation and the observed values of CA the values shown in Table XI were computed for the various conditions shown when the clipping level CL was at 124 db.

For other clipping levels

$$\alpha_C=\alpha_C\ (\text{for } CL=124)+124-CL). \tag{19}$$

The abscissa for the observed data is then $\alpha-\alpha_C$. Since α_C was chosen somewhat arbitrarily, it was decided to plot the usual α *vs* S_W plots but show the position α_C by a heavy vertical line.

The solid lines in the Figs. 3–8 give the calculated articulation scores, the upper ones for the no noise condition, and the lower ones, for the noise condition specified on the figure. The calculated points above the gain α_C were calculated as though no clipping were present. The points should agree with the lower solid curve for gains below α_C.

For levels above α_C the speech has a distortion (overloading) not taken into account in the calculation so the observed points should be below the curve for values of α higher than α_C.

In Figs. 3 and 4 are shown the results for two cases of mixed deafness. In Figs. 5 and 6 are similar curves for two cases of conductive deafness. In Figs. 7 and 8 are shown the results for three cases of nerve deafness. The audiogram is given in each case at the top of the figure.

Calculations were made for all the cases given in *Hearing Aids* and the above results are typical. The calculated and observed results were within the observational error except for one case; namely listener $WW-R$. For this case the Harvard observers found the hearing loss for speech by using spondee lists to be 56 db and by using PB lists to be 57 db, but the audiogram gave 79 db, a discrepancy of 22 db which seems to indicate that the audiogram showed too great a hearing loss.

The agreement between calculated and observed results is so good that one is justified in using the philosophy underlying the method of calculation for obtaining fundamental information for the design of a hearing aid for a listener having any amount and kind of deafness. To do this is not a straight forward or simple procedure. All of the factors of the articulation index A, namely F, V, and E must be considered. For listeners of normal hearing the gain can be such that V and E are unity, so the criterion of the goodness of the response of the system is expressed by the value of

TABLE IX. Values of masking levels β when $\alpha=-37$ db.

$f=$	250	500	1000	2000	4000	8000
$\beta(-37)=$	53	62	59	61	57	38
$\beta(0)=$	90	99	96	98	94	75

TABLE X.

System		$f=250$	500	1000	2000	4000	8000
Flat	$\beta-\alpha$	$=90$	99	96	98	93	75
HP-6		$=62$	77	79	87	87	72
HP-12		$=41$	60	69	83	86	72
LP-6		$=84$	79	80	85	65	41
LP-12		$=83$	85	71	61	46	15

F. This is not so with deafened listeners where the gain α_t corresponding to the tolerable level is reached before it is large enough to make the factor V equal to unity. Generally it will be found that the best response R is given by

$$R=\beta_c+r\beta_n, \tag{20}$$

where the fraction r lies between 0.2 and 0.4. For example, for listener $MC-L$ the values in Table XII were computed by the more exact method. The values in Table XII correspond to the gain α_t which corresponds to the maximum tolerable speech level at the listeners ear. As the level is lowered the factor E becomes higher and the factor V becomes lower, but the latter at a faster rate.

It is seen that any of the systems having values of r from 0 to 0.3 gives about equally good results. The one with $r=0$ corresponds approximately to the Harvard HP-6, and the one with $r=0.2$ corresponds approximately to HP-12. It will be seen from F 197 that these two systems give about equally good results, and are definitely better than any of the other systems. The system labeled "FLAT" slopes downward about 15 db from 500 cps to 4000 cps and should give poorer results, and the observed values verify this. Similar conclusions are reached concerning listener JH-L and verified by the results of Fig. 8. Consider the two conductive loss cases. For the listener HM-R, the ideal response should drop about 10 db from 500 cps to 4000 cps. This corresponds approximately to the Flat system, and the tests show that the Flat system gives the best results. The same conclusions are reached for the listener RR-R.

Similar for listener FB-L the response $R=\beta_c+0.3\beta_n$ gives one which is closest to HP-6, the one which gave the best articulation. Finally, for listener DL-L, the response

$$R=\beta_c+0.3\beta_n$$

gives

		500	1000	2000	4000	8000
	$T=250$	500	1000	2000	4000	8000
	$R=36$	32	44	33	15	15
Flat	$R=42$	46	43	37	31	30
LP-6	$R=52$	52	43	30	19	12

TABLE XI

System	Values of α_C when $CL=124$ $S/N=\infty$	15	10	5
Flat	−14	−15	−17	−18
HP-6	3	0	−2	−3
HP-12	6	4	1	−4
LP-6	−5	−6	−6	−7
LP-12	−2	−2	−3	−3

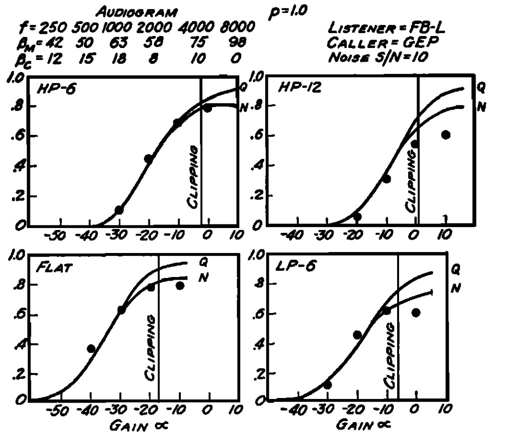

FIG. 3. Articulation gain curves for listener FB-L and noise condition $S/N=10$ (mixed deafness).

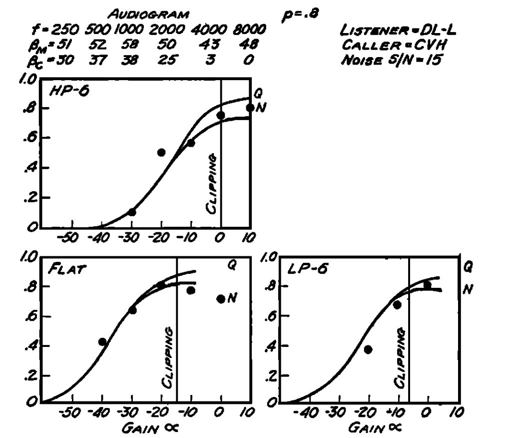

FIG. 4. Articulation gain curves for listener DL-L and noise condition $S/N=1t$ (mixed deafness).

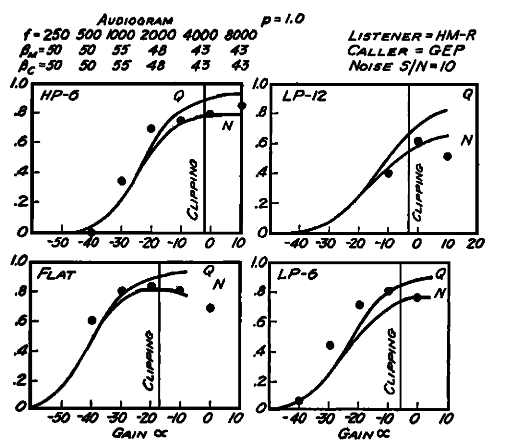

FIG. 5. Articulation gain curves for listener HM-R and noise condition $S/N=10$ (conductive deafness).

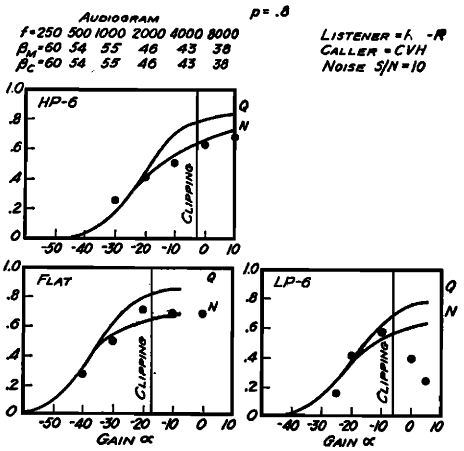

FIG. 6. Articulation gain curves for listener PR-R and noise condition $S/N=10$ (conductive deafness).

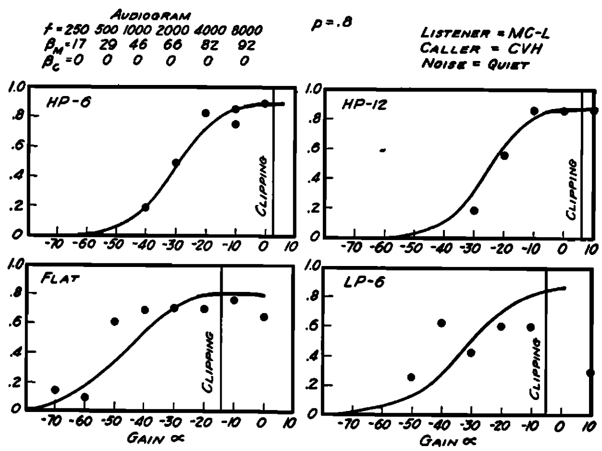

FIG. 7. Articulation gain curves for listener MC-L and noise condition quiet (nerve deafness).

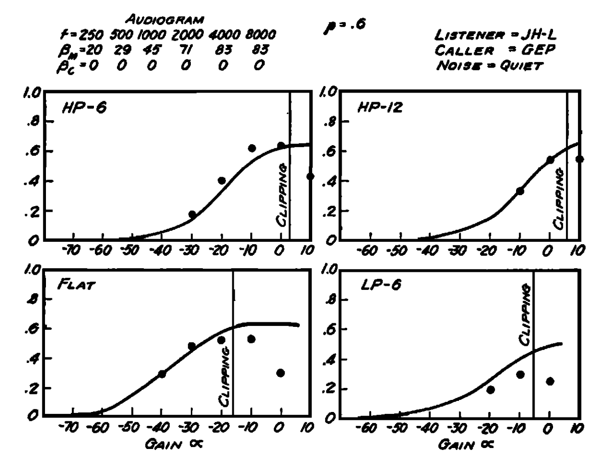

FIG. 8. Articulation gain curves for listener JH-L and noise condition quiet (nerve deafness).

It is seen that this prescribed response is between the Flat and the LP-6 and should give slightly better results than either of these two systems. So as a first

TABLE XII.

r	R	α_t	F_c	F_m	F	E_c	V_c	A(max)	S_w(max)
0	0	52	1.0	0.735	0.912	0.83	0.99	0.747	0.83
0.2	$0.2\beta_n$	40	0.99	0.833	0.938	0.83	0.97	0.756	0.85
0.3	$0.3\beta_n$	33	0.981	0.871	0.944	0.83	0.93	0.73	0.82
0.5	$0.5\beta_n$	19	0.997	0.920	0.958	0.83	0.88	0.70	0.80
0.7	$0.7\beta_n$	4	0.911	0.976	0.933	0.83	0.72	0.56	0.67
1.0	β_n	−20	0.796	1.0	0.864	0.83	0.64	0.46	0.54

trial one uses

$$R=\beta_c+0.3\beta_n, \tag{21}$$

and then calculate F, E, and V, at the tolerable limit which is given by a gain

$$\alpha_t=118-\beta_t-\bar{R}_2, \tag{22}$$

where $\bar{R}_2$ is the average of the two highest values of R from Eq. (19) of the three values at 500, 1000, and 2000 cps. It is interesting to compare the tolerable gains α_t as shown in Table XIII with those values of α_c, the clipping gains used in the tests at Harvard.

TABLE XIII.

System	Flat	HP-6	HP-12	LP-6	LP-12
Calculated α_t=	−8	10	17	5	11
Values given for α_c in hearing aids	−14	3	6	−5	−2

This then gives a method of determining the response characteristics and maximum gain necessary for a hearing aid to be used by a listener having any amount and kind of deafness. It also indicates that a limiter of some sort should be placed in the set so that it stops the speech levels from reaching values greater than 118 db plus the following peak values:

f=	250	500	1000	2000	4000	8000
peak value	10	12	8	5	1	1

This means that the pressures levels produced by the receiver on the standard coupler should not be permitted to go higher than 128, 130, 126, 123, 119, and 119 db at the six frequencies, respectively. This will be accomplished if a general cut-off level of 128 db be used.

ACKNOWLEDGMENT

When this paper was started some three years ago it was expected that Dr. R. H. Galt would be a joint author. Since he was unable to continue as such, I wish to acknowledge here his early work on the paper and also his helpful suggestions and criticisms for improving it.

The figures are from the second edition of the author's book entitled *Speech and Hearing in Communication*, to be published in 1952 by D. Van Nostrand Company, Inc., New York, New York.