Loudness functions under inhibition[1]

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In both vision and hearing, a masking or inhibiting stimulus increases the slope (exponent) of the power function that relates sensation to stimulus. The power transformation applies only to the inhibited part of the function where the signal is fainter than the masking noise. Where the signal equals the noise, the function shows a discontinuous knee. Experiments were undertaken to see whether the loudness of a tone of 1000 Hz in a white noise would follow a model based on a constant signal-to-noise ratio at two locations, at the effective threshold and at the knee where the inhibited function meets the uninhibited function. The data accord with the slopes (exponents) generated by the model. The same model gives a fairly good account of the recruitment functions for ears suffering from cochlear involvement (e.g., Méniere's disease). Regardless of degree of hearing loss, loudness recruitment reaches normal when the tone (1000 Hz) is about 30 dB above the affected threshold.

In a previous paper (Stevens, 1966) it was shown that in both vision and hearing the effect of a masking or inhibiting stimulus is to increase the slope (exponent) of the power function that relates sensation to stimulus. The effect, which can be described as a power transformation, applies only to the part of the function that is inhibited by the masking stimulus. At the level where the inhibited function meets the uninhibited function, there results a knee, as pictured in Fig. 1. In the visual domain, only stimuli that are fainter than the masking stimulus, often called the inducing stimulus, suffer inhibition (Stevens, 1961a; Horeman, 1965; J. C. Stevens, 1967). The published evidence in hearing shows a less clear-cut knee than is demonstrable in vision, probably because a sharp stimulus separation is not possible in the ear. Nevertheless, to a first approximation, a similar principle seems to hold: Stronger stimuli inhibit weaker stimuli, but not vice versa. Furthermore, in both vision and hearing, the steepness of the inhibited power function (in log-log coordinates) increases with the strength of the masking stimulus.

The present study was designed to explore the loudness function for a pure tone when the tone is masked by various levels of white noise. The data seem to accord with a rather simple principle concerning the signal-to-noise ratio at two locations on the masked function. Both at the effective threshold and at the level where the tone emerges from the masking inhibition, the signal-to-noise ratio S/N is constant. The masked loudness function therefore extends over a fixed number of decibels, regardless of the degree of masking. A similar invariance has been found in some of the recruitment functions for ears suffering from cochlear involvement (e.g., Ménière's disease). Regardless of the amount of hearing loss, the loudness typically reaches the normal level when the tone (1000 Hz) is about 30 dB above the affected threshold.

The main features of the proposed model for the relations among the several variables—noise level, threshold shift, and slope (exponent) of the inhibited power function—can be illustrated by the diagram in Fig. 2. In the absence of an inhibiting noise, an equal-loudness function based on matches between one tone (ordinate) and a similar tone (abscissa) would normally follow the dashed line. In the presence of various levels of masking noise, however, the loudness of the inhibited tone follows one or the other of the steeper lines. The geometry is such that the slope of the inhibited function is a linear function of the level of the masking noise (in decibels). As pictured in Fig. 2, there is a constant 30-dB difference along the abscissa between the top and bottom of each masked function. Also, the signal-to-noise ratio is constant at both the top and the bottom of each masked function. As it turns out, the slopes (exponents) of the lines in Fig. 2 agree rather well with the slopes (exponents) of the inhibited loudness functions for a tone of 1000 Hz masked by a broad band of noise.

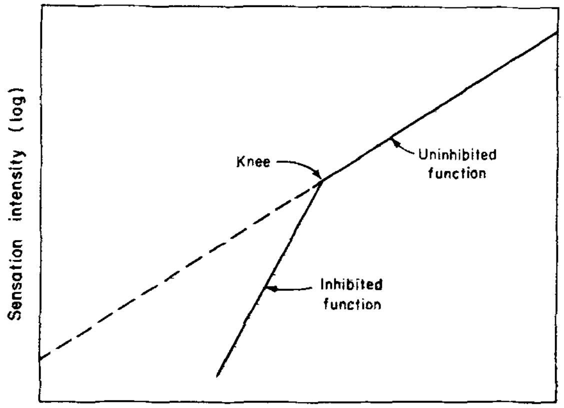

Fig. 1. Schematic diagram to illustrate how inhibition produced by masking or glare increases the slope (exponent) of the psychophysical power function. A given inhibiting stimulus affects only stimuli weaker than itself. The overall psychophysical function then consists of two segments, both of which are power functions. The intersection of the two segments forms a knee at the critical level where inhibition ceases. With no inhibiting stimulus present, the growth of sensation would follow the dashed line.

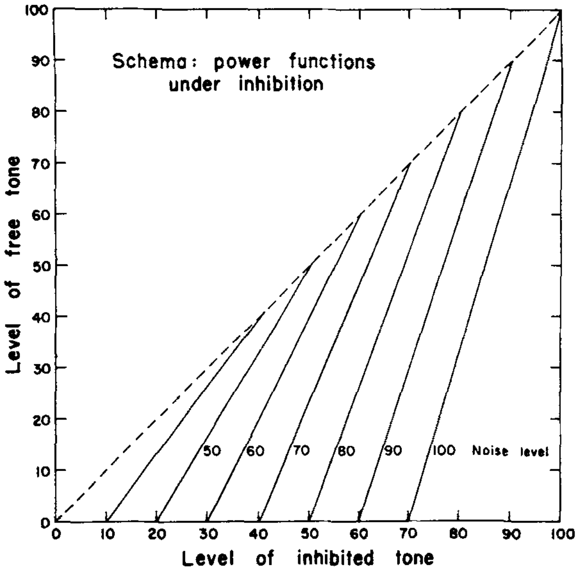

Fig. 2. Schematic model showing how the slope (exponent) of the loudness function depends on the level of the inhibiting noise. With zero inhibition, a loudness match between the free, unmasked tone (ordinate) and the inhibited tone (abscissa) would fall on the dashed line. Inhibition causes the slope of the function to increase. The slope of the inhibited function is a linear function of the inhibiting noise level. The inhibited function extends from the effective threshold to its intersection with the dashed line, at which point the noise level is equal to the level of the inhibited tone. For all the functions, the knee of the intersection occurs at 30 dB above the threshold of the inhibited tone.

EQUATING OF TONE AND NOISE

The first experiments in the present series followed the paradigm of photometry. The brightness balances made in photometry usually concern a target field and a comparison field, both presented simultaneously. One of the two fields is adjusted until the two fields appear equal in brightness. The point of equal brightness occurs at the knee where the two segments of the brightness function intersect. The discontinuity at the point where the inhibited part meets the uninhibited part of the function is plainly evident in a photometer, provided the two luminous fields have the same color (hue). If the hues differ, the transition from the inhibited to the uninhibited function loses much of its dramatic sharpness.

When a tone and a white noise, both present simultaneously, are equated in loudness, the process resembles in many ways the brightness matching of two different hues. Although the tone and the noise cannot be separated spatially, as can the two fields in a photometer, the tone and the noise differ distinctively in quality and their individual loudnesses can be judged without great difficulty. The process of equating the two loudnesses is aided by the fact that when one excitation is made stronger, it inhibits the weaker one, just as the greater brightness inhibits the weaker brightness in a photometer.

Procedure

A tone of 1000 Hz and a noise were mixed electrically and delivered simultaneously to the listener by PDR-8 earphones in sponge neoprene cushions MX-41/AR. A wide-band noise, 75 to 9600 Hz, and a narrow-band noise, 925 to 1275 Hz, were used in different parts of the experiment. Loudness balances were made in both directions; the observer adjusted the tone to match the noise, and he also adjusted the noise to match the tone. He made the adjustment by turning a "sone potentiometer" (two 2000-ohm potentiometers ganged and cascaded). When the tone was to be adjusted, the instructions read:

> In this experiment you will hear a tone and a noise. Your task is to adjust the loudness of the tone to make the tone and the noise sound equally loud. Adjust the loudness of the tone by rotating the knob in front of you. Try to approach equality by bracketing, that is to say, by setting the tone both louder and softer than the noise.

The overall levels of each of the two stimuli were determined with the aid of a root-mean-square voltmeter (Ballantine 320). Each of 20 Os made two adjustments of the tone to match the noise and two adjustments of the noise to match the tone in each part of the two experiments.

Results

The decibel averages of the loudness balances are shown in Figs. 3 and 4. The dashed line in Fig. 3 shows the locus of equal sound pressure level (SPL) for tone and noise. The solid line was drawn to

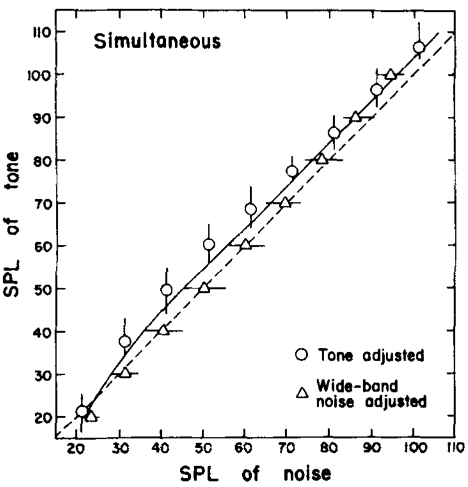

Fig. 3. A tone (1000 Hz) was matched in loudness to a white noise (75 to 9600 Hz). Tone and noise were both present simultaneously. The tone was adjusted to match the noise (circles) and the noise was adjusted to match the tone (triangles). The lines through the points indicate the interquartile ranges for the 40 adjustments, two by each of 20 listeners. The dashed line shows the locus of equal SPL for tone and noise.

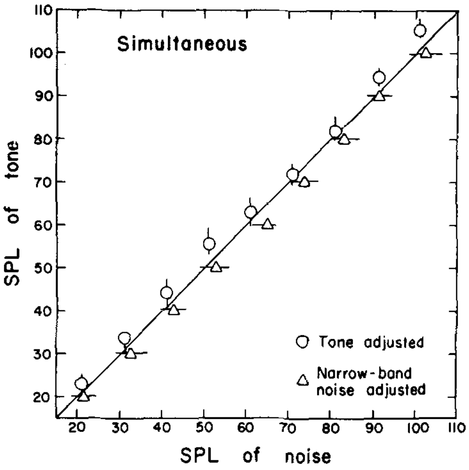

Fig. 4. Loudness balances between a tone (1000 Hz) and a narrow band of noise (925 to 1275 Hz). Tone and noise were presented simultaneously, as in Fig. 3.

represent the approximate consensus of the two parts of the experiment. As has been demonstrated in other experiments (cf., Zwicker, 1958), the loudness balances differ, depending on whether the tone or the white noise is adjusted. The difference in Fig. 3 is smaller than it was in Zwicker's experiment, where the tone and noise were presented successively rather than simultaneously. The simultaneous presentation seems also to produce slightly less variability than was evident in Zwicker's study. The lines through the points in Fig. 3 mark the extent of the interquartile ranges. The downward curvature near the bottom of the curve in Fig. 3 is typical of loudness matches between tone and noise (Stevens, 1955, 1961b). As threshold is approached, the loudness of a white noise falls more rapidly than the loudness of a tone.

As shown in Fig. 4, the matches between the tone and the 350-Hz band of noise suggest that the point of equal loudness occurs when the tone and the noise band have the same SPL. The straight line shows the locus of equal SPL. The width of the noise, measured between the half-power points, was approximately equal to two critical bands (Zwicker, Flottorp, and Stevens, 1957). The lines through the points show that the interquartile ranges were smaller when the narrower band of noise was used. The discrepancy that depends on which stimulus, tone or noise, is adjusted was still evident with the narrow-band noise. A similar kind of "adjustment error" has occurred in numerous experiments. On the average, over the low and middle ranges, the stimulus controlled by the O is set relatively too high.

In addition to the adjustment error, there often occurs a regression effect (Stevens & Greenbaum, 1966). The regression effect is noticeable in Fig. 3 where the regression line determined by the circles is less steep than the regression line determined by the triangles.

The foregoing experiments show that a tone and a noise may be made to sound equally loud under simultaneous presentation. Equality occurs when the tone and a narrow-band noise (two critical bands) have about the same SPL. With a wide-band noise, at an overall SPL above about 40 dB, the tone must be 3 or 4 dB more intense to be judged equal to the noise. The equal-loudness results in Fig. 3 suggest that somewhere in the vicinity of the S/N ratio of 0 to 4 dB, the transition illustrated by the knee in Fig. 1 may be expected to occur. When the wide-band noise is louder than the tone, the tone is inhibited; when the tone is louder than the noise, the noise is inhibited. At the level where tone and noise appear equally loud, there is presumably a partial inhibition of each stimulus by the other, because the separation between two stimuli in the ear is not sharp. The excitation patterns overlap in a complex manner. In the eye, however, the partial overlap of two stimuli can be avoided, and there we find that two equally bright fields have no effect on one another.

LOUDNESS BALANCES WITH ALTERNATE PRESENTATION

For purposes of comparison, the loudness of a tone (1000 Hz) and a wide-band noise (75 to 9600 Hz) were equated under alternate presentation. The sequence was tone for 1 sec, silence for 0.5 sec, noise for 1 sec, silence for 0.5 sec, and then repeat. Eighteen Os each made three adjustments of tone to match noise and three adjustments of noise to match tone.

The results are shown in Fig. 5. Separate regression lines have been drawn for the two parts of the experiment in order to illustrate the regression effect referred to above. The slope of the best-fitting regression line is different depending on which variable the O controlled. The data represented in Fig. 5 are less extensive than those represented in Fig. 3. On the average, the level of the tone was made 2 or

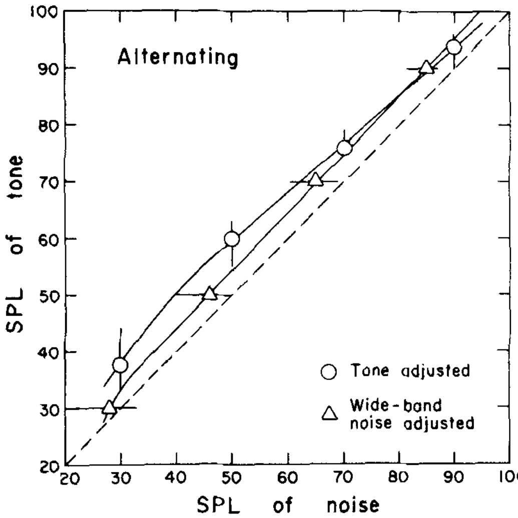

Fig. 5. Loudness balances between a tone (1000 Hz) and a white noise (75 to 9600 Hz) presented alternately. Each of 18 listeners made three adjustments of tone to match noise and noise to match tone. The lines through the points show the interquartile ranges.

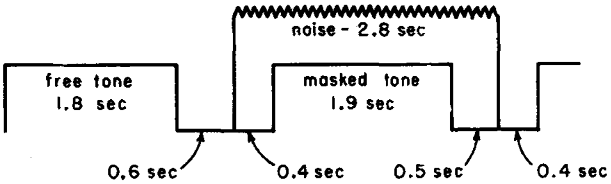

Fig. 6. Time sequence employed for the alternate presentation of the free, unmasked tone and the tone masked by a noise.

3 dB higher when the stimuli were presented in alternating sequence instead of simultaneously.

LOUDNESS BALANCE BETWEEN FREE AND INHIBITED TONES

The form of the masked loudness function was determined by means of a loudness balance between an isolated tone, free of noise, and a masked or inhibited tone.

Procedure

The free, isolated tone (1000 Hz) and the tone (1000 Hz) in noise (75 to 9600 Hz) were presented alternately in a repetitive cycle. The sequence, controlled by a motor-driven timer, was as shown in Fig. 6. In order to help the O to hear and identify the masked tone at faint levels, it was turned on after the beginning of the noise and off before the end of the noise. For the part of the experiment in which the free, unmasked tone was adjusted to match the loudness of the tone immersed in noise, the written instructions were as follows:

> In this experiment you will hear two tones, one after the other. One of the tones will be masked by a noise. Your task is to adjust the loudness of the unmasked tone to make both tones sound equally loud. Adjust the loudness of the unmasked tones by rotating the knob in front of you. Try to approach equality by bracketing, that is to say, start by setting the isolated tone both louder and softer than the tone in the noise.

In another part of the experiment, the listeners adjusted the masked tone to match the isolated, unmasked tone. The O made his adjustments by means of a sone potentiometer.

A total of 12 Os served in the experiment to determine the masked loudness function for a tone of 1000 Hz in the presence of a white noise at various levels. Complete data for all levels of the masking noise were obtained from two listeners. As many as nine listeners were used for the middle-range masking noises. Stimuli were delivered through PDR-8 earphones mounted in circumaural cushions (Stevens, 1946).

Results

Figure 7 shows the results obtained when the tone in the quiet was adjusted to match the loudness of the tone in the noise. Each point is based on a match by at least four and as many as nine listeners. The lines fitted to the points were constrained only as regards slope, not intercept. The slopes were fitted as a complete family, which is to say that a change of one slope entailed a change of all the others. Given a model like that schematized in Fig. 2, a question arises whether all the data can be simultaneously accommodated by a set of slopes determined by the model. The slopes are those determined by the assumption that S/N is constant at the effective threshold, and that the knee occurs 30 dB above that point. The slopes of the resulting family of lines appear to fit the data reasonably well.

Above the knee, which is clearly evident in only a few of the functions, the loudness function has been drawn parallel to the dashed line, i.e., with a slope of 1.0. It is clear that the knee does not fall on the dashed line, as it does in the schema of Fig. 2. In the actual loudness matches, the departure of the intercepts from the positions suggested by Fig. 2 increases as the masking noise is increased. Nevertheless, the slopes behave as predicted.

Figure 8 shows the results obtained when the listeners adjusted the tone in the noise to match the tone in the quiet. Each point is based on a match by three Os, except for the noise levels 50 and 90 dB, where two Os were used. The variability when the masked tone was adjusted in this part of the experiment was small, and more Os did not seem needed.

Like those in Fig. 7, the slopes of the lines in Fig. 8 were made to meet the criterion imposed by the model. Compared to Fig. 7, several small dif-

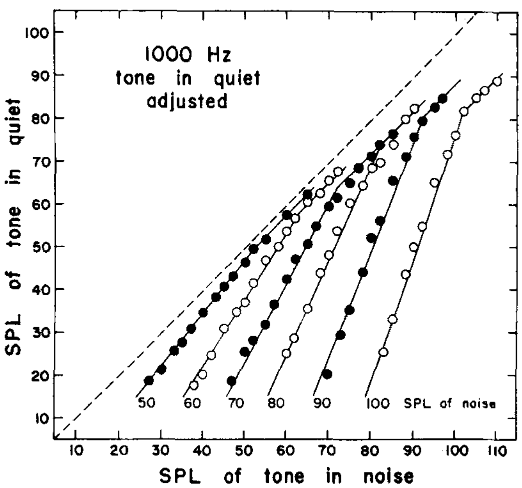

Fig. 7. Masked loudness functions obtained by adjusting the free, unmasked tone to match the loudness of a tone inhibited by various levels of white noise. The slopes of the lines through the points were determined and fitted as a complete family, in accordance with Fig. 2. Since the coordinates are logarithmic (decibel), the slopes determine the values of the exponents of the masked loudness functions *relative* to the value of the exponent for the tone in the quiet.

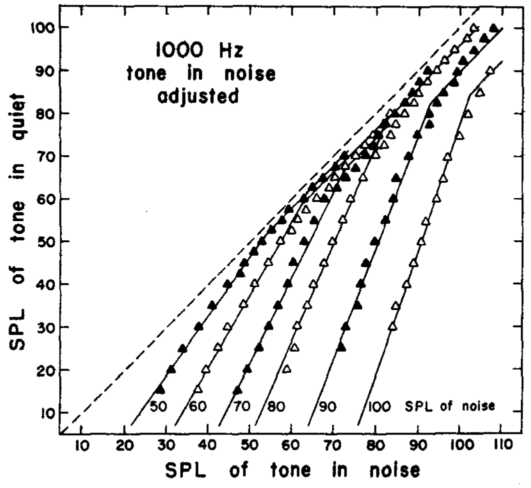

Fig. 8. Masked loudness functions obtained by adjusting the masked tone to equal the loudness of the tone in the quiet. As in Fig. 7, the family of slopes was derived from the model in Fig. 2. The slopes in Fig. 8 are all slightly steeper than the corresponding slopes in Fig. 7.

ferences are evident in Fig. 8. All the slopes in Fig. 8 are slightly steeper, as the ever-present regression effect would lead us to expect. Correspondingly, the effective threshold is lower in Fig. 8, and the knees of the functions are somewhat closer to the dashed line. Nevertheless, the intercepts remain displaced.

The procedure of fitting the families of slopes to the data in Figs. 7 and 8 involved trial and error. The fit achieved, although good, is not necessarily the best that could be achieved under the constraints imposed by the working hypothesis illustrated by Fig. 2. The final fitting can be described as follows. The knee was found to occur at the point where the tone was approximately 2.5 dB above the SPL of the noise. That point was marked on the dashed line in both Fig. 7 and Fig. 8 for each level of noise. Sets of effective thresholds, each threshold a fixed number of decibels lower (along the abscissa) than the corresponding knee, were then sought. The effective threshold chosen for Fig. 7 had an ordinate value of 15 dB; that for Fig. 8 had an ordinate value of 7 dB. The horizontal distance from threshold to knee was 30 dB for both sets of data. Lines were drawn from threshold to knee in order to define the slopes. The goodness of the slopes was then tested by transposing the lines to the data points, keeping the slopes constant.

There are two arguments for using the effective thresholds, as defined above, rather than values of measured thresholds, like those of Hawkins and Stevens (1950). One argument is that a threshold measured by a given set of operations may not be appropriate to an experiment involving a different set of experimental operations. The other argument is that in Figs. 7 and 8 two different effective thresholds are obviously needed to represent the data. The regression effect creates a need for two different values to serve as the effective lower limits of the functions.

The systematic displacement of the intercepts in Figs. 7 and 8 may have several causes. Some of the Os noted that the tone in the quiet could not be made to sound exactly like the tone in the noise. The tone in a loud noise sounds definitely higher in pitch. Even more striking to some Os was the greater apparent density or compactness of the tone in the noise, especially when the noise was intense. The matching level chosen by the listener has, therefore, and element of arbitrariness, for it depends on what aspect of the tone the listener weighs most heavily.

A more important factor in the displacement of the intercepts may be the possibility that, at the higher levels, the tone and the noise produce more mutual inhibition on each other. The effect may be visualized as a geometric relation between the excitations. When both are intense, the spread of the excitation due to the tone is presumably overlapped by a large part of the excitation due to the noise. Thus the noise is able to mask more of the wide-spreading skirts of the tonal excitation. At the point where the tone and its masking noise appear equally loud (Fig. 3), the tone is, in fact, less loud than a tone of the same SPL in the quiet. Yet it is presumably at the point of loudness equality between tone and noise that the critical knee occurs in the masked loudness function. Above that point the tone, becoming louder than the noise, begins to inhibit the noise more than the noise inhibits the tone.

An instructive experiment is to set equal the SPLs of all three signals—tone in quiet, tone in noise, and noise—and then to vary the overall level by means of an attenuator immediately in front of the earphones. At low levels the tone in the quiet sounds approximately equal in loudness to the tone in the noise. As the overall level is raised, the loudness of the tone in the quiet appears to grow more rapidly than the loudness of the tone in the noise. When the SPLs of the three stimuli reach 100 dB, the difference in loudness becomes clear and obvious. The tone in the quiet then sounds roughly two or three times louder than the tone in the noise.

The masked loudness functions in Figs. 7 and 8 confirm the theory advanced earlier (Stevens, 1966) that masking inhibition produces a transformation belonging to what has been called the power group (Stevens, 1959). The inhibited loudness functions continue to be power functions, as shown by the fact that the data in Figs. 7 and 8 may be adequately represented by straight lines. The value of the new exponent produced by the power transformation appears to increase as a linear function of the SPL of the noise.

It should be noted here that the masked loudness functions for speech in noise do not fit the model in Fig. 2. Although the signal-to-noise ratio is constant at the effective threshold, the data do not exhibit a knee at a constant signal-to-noise ratio. As a consequence, the slopes (exponents) of the power functions for masked speech do not increase in proportion to the level of the masking noise (Stevens, 1966).

EFFECT OF NOISE BANDWIDTH

When the masking noise is reduced in bandwidth, the masked loudness functions for 1000 Hz tend to become slightly steeper. The published data are not always easy to compare in this regard, but they seem to show that, when the noise is reduced to the width of an octave, the functions are steeper than when the noise is a wide band.

The slope of the loudness function under narrow-band inhibition was studied in the present experiment by means of an octave-band masking noise (600 to 1200 Hz at 80 dB overall SPL). Two Os adjusted the tone (1000 Hz) in the noise to match the tone in the quiet. The obtained slope was about 3.0 in the decibel coordinates. The corresponding line in Fig. 8 (80-dB noise) has a slope of about 2.5. The curve in Fig. 8 for the 90-dB noise (a noise that would have more nearly the same level per unit bandwidth as the octave band at 80 dB) has a slope of about 2.7. The slope obtained with the wide-band noise at 100 dB is about 3.0.

EFFECT OF SIGNAL FREQUENCY

With the wide-band masking noise at two different levels, 70 and 80 dB overall SPL, experiments were conducted with a tone of 250 Hz. The purpose was mainly to see whether the masked function at 250 Hz would prove to be a power function. The data of Jerger and Harford (1960) had suggested otherwise. Two Os adjusted the 250-Hz tone in the noise to match the same tone in the quiet.

The results are shown in Fig. 9, where each point is based on 8 to 10 adjustments. The functions show that the same kind of power transformation occurs at 250 and at 1000 Hz. The amount of inhibition is less, however, at 250 Hz, as shown by the flatter slopes in Fig. 9 relative to the corresponding functions in Fig. 8. The irregularity in the function obtained by Jerger and Harford is not apparent in Fig. 9.

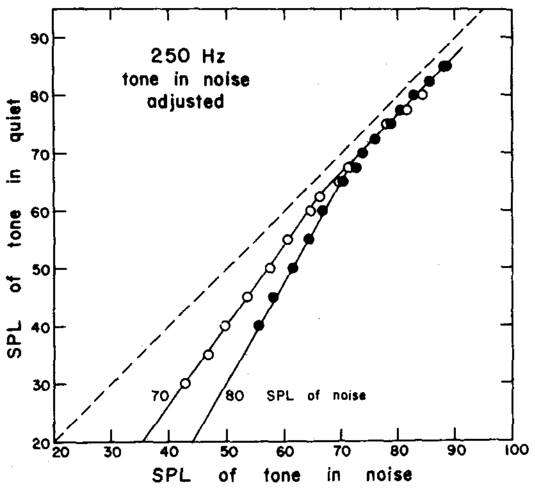

Fig. 9. Masked loudness functions for a tone (250 Hz) and a white noise (75 to 9600 Hz).

NARROW-BAND NOISE AS SIGNAL

A white noise was passed through a narrow filter (General Radio 1% Wave Analyzer 1568 A) in order to obtain a signal that could be substituted for the pure tone. The question was whether the narrow band would give different results. In particular, there was a possibility that an irregularly modulated signal might be easier for the listener to judge. The Os found that the narrow band presented about the same difficulty as the pure tone.

The masked function was measured for a wide-band masking noise at 70 dB SPL. The functions produced with the signal centered at 1000 Hz were very similar to the 70-dB functions in Figs. 7 and 8. With the signal centered at 500 Hz, the functions had slightly flatter slopes but were otherwise similar.

HEARING LOSS

The masking of a 1000-Hz tone by a white noise produces a power transformation involving a change in the exponent of the loudness function. The change is much like that produced by some kinds of hearing loss, especially those that result from a widespread cochlear involvement. Indeed, the quantitative similarities are too striking to be easily dismissed, for it appears that a family of functions like those in Fig. 2 provides a fairly accurate model for the recruitment functions determined on certain groups of hard-of-hearing patients.

Miskolczy-Fodor (1960) collected "about 300 loudness matching results in cases of complete recruitment with hearing losses of 40, 50, 60, and 80 dB . . ." Despite the scatter of his data, the central trend was sufficiently clear for him to plot a function relating hearing loss to the slope of the recruitment function. The steepness of the slope increases with hearing loss in essentially the same manner as the steepness varies in Fig. 2. Recruitment in the hard-of-hearing ear is "complete" when the tone is increased about 30 dB above the hard-of-hearing threshold.

It should be observed that loudness balances performed on patients show much scatter and variability. Variability produces an inevitable effect of rounding the knee at the intersection where the recruitment function meets the normal function. The same type of rounding occurs when the recruitment is produced by a masking noise as in Figs. 7-9. For a perfectly sharp knee to be observed in every experiment it would presumably be necessary to reduce all sources of variability to zero. In some patients, of course, there may be factors that give the loudness function

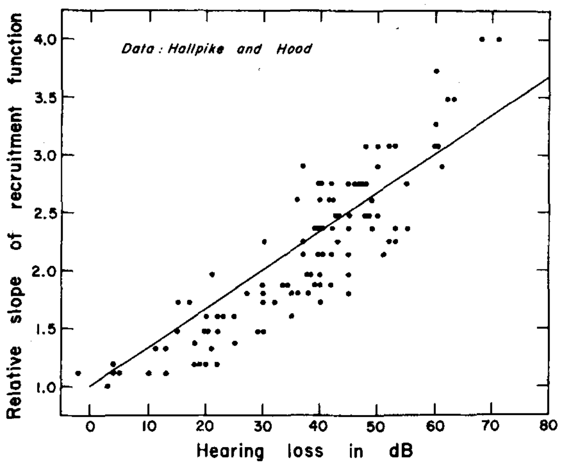

Fig. 10. Each point represents the slope of a recruitment function obtained from a patient with a unilateral hearing loss due to Ménière's disease. The slopes of the recruitment functions increase very roughly as a linear function of the degree of hearing loss. The line through the 103 points shows the locus of the predicted values according to the model in Fig. 2.

a different shape entirely. All departures from the schema in Fig. 2 are probably not due to variability alone, but the sharpness of the knee itself is particularly sensitive to variability.

Hallpike and Hood (1959) studied 200 cases of unilateral deafness due to Ménière's disease. In all cases the recruitment was said to be complete. Measurements were made at 500, 1000, 2000, and 4000 Hz. The loudness recruitment curves were power functions, for, as the authors say, "...all but a very few took the form of a straight line with clearly defined recruitment angles." The authors measured the angle of the recruitment function, relative to the horizontal abscissa, rather than the slope of the function (the tangent of the angle). The tangent of the angle is the more usual measure, for it gives directly the slope, and hence the exponent, of the power function.

The angles measured by Hallpike and Hood at 1000 Hz were read from their graph (3a) and converted to slopes. The resulting slopes are plotted in Fig. 10. Each of the 103 points represents a loudness function measured by matching the loudness in the affected ear to the loudness in the normal ear. Three points that fell outside the limits of ±2 standard deviations on the published graph were omitted. The line through the points in Fig. 10 is the line determined by the schema in Fig. 2, provided the abscissa of Fig. 2 is interpreted as hearing loss and the ordinate as sensation level in the normal ear. The parameter, noise level, in Fig. 2 is not relevant to the present purpose.

To the extent that the line in Fig. 10 can be said to represent the data, it appears that recruitment is complete at 30 dB above the hard-of-hearing threshold. The 30-dB recruitment range is independent of the amount of hearing loss. The scatter of the data obtained on hard-of-hearing patients remains large, but the slopes of the recruitment functions tend generally to accord with the same model that predicts the slopes of the masked loudness functions when the inhibiting stimulus is a wide band of noise.

Hallpike and Hood note that "the essential morbid anatomical change found within the cochlea in Ménière's disease is a distention of the endolymph containing scala media." The resulting degenerative changes in the cochlea follow a "diffuse pattern." There seems to result a process that resembles inhibition, a process that shows a functional similarity to that produced by a wide-band noise.

Presumably the site of the inhibitory process is the sensory receptor, for, as Hallpike and Hood observe, loudness recruitment "is absent in deafness due to organic affections of the cochlear nerve fibers." That observation may have a bearing, at least indirectly, on the hypothesis that the power transformations produced by glare in vision and masking in hearing may represent end-organ processes.

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Notes

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