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Loudness
Discrimination

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Discrimination

Introduction

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Nothing surely could be more useful to our understanding of how human beings respond to acoustic stimuli than a clear notion of the effect of changes in the energy input. In biology we are more familiar with instances of response to environmental change than to steady states. A large part of the economy of animal life depends upon the individual's being sensitive to very minute fluctuations in sensory equilibria.

The measurement of loudness difference limens at various frequencies and loudnesses would seem to be a rather simple and straightforward process. Through the years, however, the absolute values reported by several experimenters have differed greatly, though the trends have generally agreed that increased loudness yields increased sensitivity. It is accepted that these differences are based upon the individual subjects, the apparatus, experimental procedures, exact stimulus conditions of energy transition from one level to another, and the particular psychometric methods involved.

It is nevertheless rather surprising that, although this general problem has been attacked many times, no really clear statement has emerged. The con-

fused status of the difference limen for loudness was recently put deliberately in its worst light by Hirsh, Palva, and Goodman (39).

This paper concerns the smallest change in the loudness of a pure tone which the normal human ear can just detect. We will refer to this change, however it is derived, by the noncommittal term ΔI unless a more precise term (several are used later on) is demanded by the context. Interest in the topic comes not only from its evolutionary importance and its inherent attractiveness to the curious worker, but also from its use in the more restricted field of psychoacoustics, where we wish to utilize the ΔI in calculating a possible scale of loudness, in comparisons with masking data, as assistance to the otologist, in calculating the total number of distinguishable tones, in interpreting nuances of speech, etc.

The modern history of loudness discrimination is generally said to begin with Knudsen (48). He summarized the work of the pre-electronic age and furnished data collected with a telephone receiver. These data are still useful, though what is now taken as a defect appeared in that he used an abrupt transition from one intensity level to another. Such a transition may introduce transients, an artifact one seeks nowadays to avoid.

Riesz (80, 81) overcame all objec-

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tions to previous work and presented data which have not been superseded. To avoid transition clicks he arranged two frequencies separated by three cycles so that at equal intensities a clear three-cycle beat appeared. If, now, one of the frequencies is gradually decreased in intensity, the beat gradually becomes no longer audible. What one has here is a case of sensitivity for one form of amplitude modulation, from which a particular ΔI can be derived. Riesz's apparatus was impeccable, his range of frequencies and intensities was wide, and although his psychophysical technique was not very fully stated, there is no reason to assume any inordinate experimental error.

The fact is, however, that the generality of Riesz's data has not always been confirmed by subsequent studies. Several workers have noted that the data may be suspect because of the use of beats (*15, 60*). This criticism seems to go beyond the century-old and now commonplace notion that a change in the experimental conditions will be followed by a change in the index of sensitivity. What we meet here head-on is the question of whether the Riesz experiment, otherwise ideal, is in fact a clearcut sample of loudness discrimination.

The numerous studies on the ΔI since Riesz will, in order to save space, not be summarized in this minute historical section, but will be referred to in the body of the paper as appropriate.

A Little Psychophysics

Since the elegant heyday of psychophysics under Fechner and later in this country Titchener (*89*), a lot of water has passed over the dam, most of it muddy. No essentially new methods for examining sensory experience have been proposed, but the standard methods have been subjected to many variations and distortions, bad as well as good. Most of the changes have been proposed to attempt to overcome the disadvantage of requiring careful judgments from careful subjects. Many shortcuts in experimental design have been used to avoid the labor of identifying and overcoming the three types of error: constant, variable, and accidental. The resulting data may be vitiated in many ways, but it cannot be denied that often time and energy are indeed saved.

Of course, for one reason or another a worker may quite justifiably choose one variant or another of a standard procedure, but he has the responsibility of pointing out the possible effects on his data. This journal has entertained comments in plenty on the quite wide differences in indexes of sensitivity depending upon instructions to the subject, whether the subject controls the stimuli, etc. And of course the psychological journals used to live on such observations. Suffice it only to add here that the distinctions called for in this paper are not pedantic or trivial but can amount to errors of interpretation of the order of magnitude of 2 or 3.

Need for Standard Terminology

One way to reduce confusion is to adopt a standard terminology for measures of the ΔI. Each major psychophysical method has its own measure, and the various measures cannot well be directly compared. But if the various measures, instead of all being called

by the generic term 'DL,' for 'difference limen,' were given separate names, there would be less tendency to compare 'DLs' by two different methods.

Resisting the temptation to coin new symbols, the writer feels that it is only necessary to utilize the terms which were current and well-defined at the turn of the century, but whose distinctions have now pretty well corroded. For differential problems in audition the three commonest measures are the following:

1. Constant Stimulus Differences. In this method, two stimuli are compared, one following the other. Subject introspects and reports 'louder,' 'softer,' 'doubtful,' or 'equal.' For some problems, only increments or decrements of the dimension are presented.

The correct term for the ΔI here is DL, or $DL_{inc(dec)}$ as the case may be. The index DL here would mean that increments and decrements had been counterbalanced and averaged. For some problems, 'equal' and 'doubtful' judgments are denied. Here the otherwise universal notion of the ΔI as the 50% point cannot hold. Jastrow in 1885 proposed the 'method of right and wrong answers' and suggested that the 75% point on the curve relating percentage errors to stimulus dimension should be taken as the limen. This has shown surprising durability. Let us call its index $DL_{75\%}$, which clearly indicates that only two choices are offered the subject (the essence of this variant) and that the 50%-correct point is chance behavior.

We would include with the symbol $DL_{75\%}$ the index derived from the often very useful variant of the Jastrow method, commonly now known as the ABX method (with of course its own variants AXB and XAB).

Another index should be mentioned in this section, the 'quantal' method; two distinct features of this method are:

a. the manner of stimulus presentation. Each stimulus is a brief increment in a steady-state signal.

b. the psychophysical method. This is actually a variant of constants but with serial exploration. Instead of a single variable stimulus, a number of increments are given consecutively and S reports in some way the percentage heard. The per cent correct is plotted against the variable stimulus intervals and the 50%-heard point is read off just as with a DL_{inc}; and the true quantal index should be designated $DL_{inc(Q)}$, or simply DL_Q if S can listen to the decrement as well.

2. Limits. The experimenter changes one stimulus dimension slowly, or changes an interval between paired stimuli, etc., until S notices a change. The change may be in the direction for a quality to become just noticeable or just *not* noticeable. It may make quite a difference. We traditionally call the first a jnd, the second a jnnd (notice these are not in caps). If, as should generally be the case, both directions are counterbalanced and averaged, the average of the jnd and the jnnd would be the JND. When, therefore, JND is used, the reader should understand that both jnd and jnnd enter the JND. But further, E may use either increments or decrements, or both, to determine jnd and/or jnnd. This too may make quite a difference. Therefore E should report jnd only if both increments and decrements were

counterbalanced; otherwise he should report jnd_{inc} or jnd_{dec}. He should do the same of course for the jnnd. By this essentially simple and time-honored practice, E can indicate in his index precisely what judgments were included.

3. Adjustments. The features of this method are that S himself controls a stimulus dimension, producing an equality in two stimuli. The traditional measure of sensitivity is the standard deviation of his 'equality' settings. It is taken for granted that the S.D. arises from an experimental design in which time-order, spatial, and other error sources are counterbalanced.

This writer cannot of course speak for others, but at least in this paper the terminology as outlined above will be used in summarizing the many sets of experimental data from this and other laboratories.

Experiment I: The DL Optimized

Introduction

Our first thought was to work over the ground on the ΔI as covered by Titchener (*89*), but with the modern resources of electronics. Our hope was to discover the finest differential sensitivity for loudness over the auditory area possessed by well-trained Ss when the psychometric and stimulus conditions were maximized.

The idea that for any particular aspect of sensory discrimination no single ΔI exists, but that each index is dependent upon method of calculation, preparation of Ss, etc., has been a platitude in experimental psychology for well over a century. But this is certainly not to say that under certain circumstances there is no preference for methods which tend to exhaust the discriminatory powers of the peripheral organ. This is presumably what Montgomery (*62*) meant in recommending the discovery of 'optimum conditions.' Our own attitudes on this question have been fully stated elsewhere (*35*).

We turned first to the method of constant stimulus differences on the basis of Titchener's summary account. Montgomery has more recently discussed the importance of the following factors, among others: the effects of transition between tones (the shorter the interval between the tones the greater the sensitivity), number of comparisons (sensitivity increases with number of presentations), control of presentation (when S controls, sensitivity increases), and type of judgment ('louder'—'softer,' 'change'—'no change').

Several months were devoted with three very experienced Ss to a systematic search for a variant of psychometric method which would simultaneously reduce inter-subject differences, reduce sources of variance contributing to any DL, and yield a relatively fine DL. A wide range of each of several parameters was meticulously tried (*78*). Most of these data have only negative meaning since in the case of each parameter we finally chose, and state here, the optimal condition.

Conditions of Testing

Two tones each 0.5 sec in duration were presented monaurally, with a 40-msec rise-fall time, and 0.5 sec interstimulus interval. This duration of tone is just long enough to yield full loudness buildup even with the weakest levels; to make it longer only wearies the well-trained S. The interstimulus interval was found which yielded a negligible (less than 0.1 db) negative time-error with our particular Ss (for other Ss, other intervals might have to be chosen).

The subject was requested to press a silent microswitch whenever he felt his physiological noise level was low and he was in a maximally receptive attitudinal condition. He was forced to judge the second tone 'louder' or 'softer.' If in doubt, he was allowed to press the switch *ad lib.* until a judgment was forthcoming.

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TABLE 1. $DL_{75\%}$ in decibels, method of constant stimulus differences, situation optimized.

| Phon Level | Subjects | | | | | | | | |
| | SES | | | CKM | | | CRP | | EBH |
	125	1000	6000	125	1000	6000	1000	6000	1000
5	.79	.87	.56	1.17	1.40	1.35	1.48	.95	.92
10	.55	.86	.60	.82	.65	1.12	.92	.79	.49
20	.38	.79	.61	.64	.68	1.38	.84	.82	.50
40	.52	.48	.62	.72	.66	1.38	.78	1.20	.47
60	.67	.51	.56	.76	.62	.91	.90	1.10	.26
80	.48	.35	.57	.60	.55	.55	.64	.50	.37

Note: Since with no time-error, as in the present case, the $DL_{75\%}$ is actually the semi-interquartile range, an estimate of the variance of these data can be had by use of the formula:

$$P.E._Q = .7867 \frac{Q}{N}$$

The $P.E._Q$ of these data vary from .036 to .007 where $N = 900$.

The distribution and range of variable stimuli throughout an experimental session were found significant. It was found best to distribute the variable steps at random rather than to start with the easier and proceed regularly to the more difficult. It was also found best to eliminate steps which are easy for S. Twelve variable steps in 0.2 db intervals were finally chosen for the final data, between plus 1.2 db and minus 1.2 db for nearly all sets, except a few for which 12 steps in 0.3 db intervals were used. Loudness levels for any frequency were selected at random for any session.

It was found deleterious to require more than 60-90 judgments in any one experimental session before a substantial rest period was taken. Each variable was presented 75 times, over a period of months to wash out incidental factors. Sensation level (SL) was carefully maintained. If days or weeks elapsed before work could be resumed, adequate warmup was instituted. Stable ΔIs were finally reached (that is, DL_{75} did not change on a complete replication).

Each $DL_{75\%}$ was thus derived from a total of 900 judgments and in our opinion represents an S's stable, asymptotic sensitivity, not necessarily merely his sensitivity over a single session or a single day. Montgomery has remarked on daily fluctuations in work of this sort.

The most reliable way to estimate the $DL_{75\%}$ was established to be to use the Müller-Urban weights. However, graphing on probit paper is about equally good.

The frequency 1000 cps was studied, with four normal-hearing Ss at SLs of 5, 10, 20, 40, 60, and 80 db. Three of these Ss made careful loudness matches between 1000 cps at each of the six loudnesses, against 125 and 6000 cps. These data were used in collecting $DL_{75\%}$ at the two extreme frequencies (only two Ss completed 125 cps). Thus the auditory area, within the limits of distortion of the PDR-8 earphone, was traversed from 125-6000 cps in six iso-sonic paths.
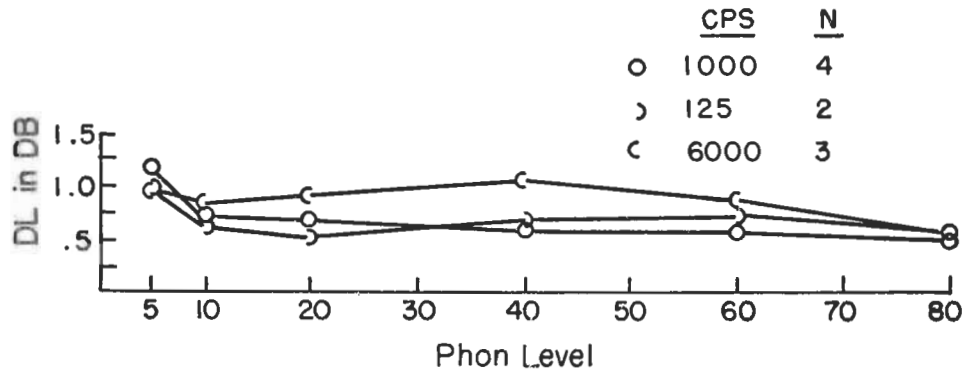
FIGURE 1. Mean $DL_{75\%}$ in db for Loudness-Memory, situation optimized.

Total distortion for continuous tones at these frequencies was kept negligible (well below 2%) as measured with a Hewlett-Packard meter, except at the loudest level at 125 cps, where for two Ss it reached 4%.

Results

The results are set forth in Table 1 and Figure 1. These show that:

1. The absolute size of the $DL_{75\%}$ is rather small; with optimal conditions the average laboratory ear (our four Ss here are by no means the most acute of our staff, as the data for CKM show) can respond to changes of the order of 0.5 db.

2. There is no effect of frequency for any isosonic contour from 125-6000 cps.

3. There is little effect of overall loudness except at the very weakest SL.

Discussion

These data are in accord with the few experiments using conditions at all comparable, but they are in sharp contrast on three counts with other experiments on the ΔI.

1. Previous studies using optimum conditions. In the pre-electronic age many studies had suggested that the human ear could detect a fairly small fraction of a decibel change in intensity, but it was usually alleged in later decades that the stimulus conditions were not impeccable, being complicated by transients and harmonics. However, Montgomery (*62*) reported a DL of 0.64 for one S, using 1000 cps and only 11 db SL. For another S listening to white noise the DL was commonly around 0.5 db depending somewhat on attention factors and method of varying the intensities. He states that these values for noise were in general representative of unpublished values for a 1000-cps stimulus.

If values for white noise are indeed to the point, then experiments can be cited (*34*) which show that $DL_{75\%}$ is never larger than 0.7 db even for 10 *in*experienced Ss at any SL down to and including 5 db.

Doughty (*17*) has provided valuable information on optimizing the DL. He showed that a smaller $DL_{75\%}$ is achieved if S is given a narrow range of variable stimuli rather than a broad range (see his Figure 9). For 1000 cps

at about 65 db SL, with two tones 1 sec long and with 1 sec interstimulus interval, three Ss yielded a mean $DL_{75\%}$ of about 0.35 db.

Pollack (74) has documented the influence of context on what we may call loudness-memory. Essentially the same results appear as have been shown (32) for the ΔF: one can eliminate the Standard of a pair altogether (the classic method of single stimuli) and S can still yield a remarkably fine judgment. With four Ss, Pollack found a mean $DL_{75\%}$ of about 0.5 db which rose only to about 0.6 db even when as much as 10 sec intervened between successive tones. This is as good as in the usual two-stimulus method (33). When a Standard was actually presented but was changed slightly in level from time to time, no deterioration in $DL_{75\%}$ was found. In such work it is evident that S can build up an internal Standard on the basis of all the stimuli he hears within a session, but he will abandon it in favor of an actual Standard if one is offered.

Pollack found two conditions which *did* cause a slight deterioration in $DL_{75\%}$: a procedure in which successive single tones increased regularly in 0.2-db steps every 0.31—20 sec, S being asked to indicate after every stimulus whether he sensed the direction 'louder' (in another series, of course, a 'softer' direction and judgment were used). This procedure yielded $DL_{75\%}$ of about 0.8 db at all interstimulus intervals up to 20 sec.

The worst procedure Pollack found was a so-called 'roving Standard' in which S judged whether Tone B was 'louder'—'softer' than Tone A, Tone C with respect to Tone B, D to C, etc. In this case the mean $DL_{75\%}$ rose

to about 1.4 db with an increase to 20 sec in interstimulus interval.

Pollack (75) has further shown how the $DL_{75\%}$ deteriorates when (instead of always giving the Standard tone at a constant loudness) it is made to vary at random between two SLs. Per cent correct for a 'loud'—'soft' judgment fell off from 76 to 65 when the two Standard intensities were randomly placed at either 82 or 98 SPL (a constant 1-db difference between all Standards and Variables was maintained). When the two SPLs of 86 and 94 were varied in blocks of 1, 2, 5, 10, 15, 25, and 50 rather than interspersed at random, the per cent correct improved regularly from 70 to 80. The $DL_{75\%}$ was not much, if any, affected by changes in audiofrequency of successive pairs of stimuli.

Woodhouse (92) clearly shows that a judgmental period of 3-5 sec is an optimum judgment time in loudness-memory. He reports a $DL_{75\%}$ as low as 0.25 db for a trained S at 150 cps.

We conclude at this point that our data confirm and considerably extend previous data to the effect that under optimal conditions the human ear can yield a relatively very small $DL_{75\%}$ of the order of 0.5 db and less over the major portion of the auditory area and is thus almost completely independent of frequency and loudness.

2. Previous studies using other conditions. A very few key studies will be cited here to show that, under some stimulus and/or judgmental conditions, results may be yielded greatly divergent from these on the counts of absolute size, effect of overall loudness, and overall frequency. Furthermore, a beginning will be made on identifying

the conditions which underlie the differences in the ΔI.

Dimmick and Olson (*15*) report a $DL_{50\%}$ of about 4.5 db at 10 db SL, but even at the loudest levels their DLs were never finer than 2.3 db. We conclude that these inordinately large figures argue in favor of forcing a response from S; about the only difference between the experiments of ours and of Dimmick and Olson's was that they allowed—encouraged?—S to respond 'equal' if no difference was clear.

On the other hand, no such explanation in judgmental terms can apply to the data of Knudsen (*48*), of Churcher, King, and Davies (*10*), and of Riesz; these data are too widely known to summarize here except to point out that they all show a poor ΔI at 10 db SL (about 2 - 2.5 db) as compared to our Experiment I (about 0.5 db) but they all show at least equally good ΔIs at 60 db and louder. We conclude that the strong effect of overall loudness in the work of these three papers must reside in the particular stimulus used. We will return to this matter later on.

In summary of this section, we conclude that either a real difference in psychophysical method, or in the acoustic manner of presenting S with an intensity change, may create a truly new test which may yield a ΔI more or less sensitive to overall loudness and to frequency as the case may be.

Experiment II: The Just Noticeable Difference In Loudness-Memory

It was at this point clear that a number of experiments would be needed to bring real explanatory order into the existing sets of data. It would be necessary to repeat some of the earlier studies, to administer several types of test to the same group of experienced Ss, to explore individual differences in large groups, and to take a long close look at some of the correlations and other inter-relationships among tests of loudness discrimination. We attacked these problems as we were able.

A first control experiment was set up to study the effects of forcing S to judge 'loud'—'soft.' We wished to present the stimuli much as was done in Experiment I, but we wished to avoid a forced choice. A combination of the methods of limits and adjustments was chosen after much preliminary effort had shown it to reduce between- and among-subject variance to a minimum.

Conditions of Testing

A pure tone was split and fed to the two channels of a shaper amplifier and associated timer. The amplifier was set to a 40 msec rise-fall characteristic and the timer set to pass a series of tones of 0.6 sec duration, with 0.6 sec intervals of silence intervening. Alternate tones were controlled by separate attenuators. Subject sat in a soundproof room with an attenuator in 0.1 db steps in each channel. Experimenter had two similar units in parallel with these. Subject first found his absolute threshold by adjustments on Channel I for one of the frequencies 125, 1000, or 6000 cps. Experimenter then selected the desired SL in Channel I for that session, and then adjusted his attenuator for Channel II so that the variable tone was either equal in loudness to, or considerably louder than, the standard tone in Channel I. Subject was asked to adjust his attenuator for Channel II to yield either a jnd or jnnd as the design called for.

Thus far the classic method of limits was followed, but a modification was found of great value. In either the ascending or the descending series, if S proceeded beyond the point he felt would be his final judgment if the method of adjustments were used, he was allowed to reverse direction and continue adjusting loudness in order to bracket the jnd as finely as possible. In this way and in this case S provided a JND about halfway between a jnd and a jnnd, with a great compression of effort on the part of E and with results negligibly different from the classic JND.

A small neon light beside each of S's two attenuators flashed when the tone controlled by that attenuator was presented. This system helped to orient S and allowed E to observe that the apparatus was operating correctly in timing and alternation.

Six or, in most cases, ten thresholds at each loudness level were collected and averaged for each S. Seven experienced Ss were used.

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TABLE 2. JND in decibels, Loudness-Memory, method of limits-adjustments.

Loudness in Sones	JDH	JJO	CKM	CEW	CEG	ARJ	BHC	Mean
				Subjects				
				1000 CPS				
.004	2.00	2.31	5.08	1.17	1.24	3.01	2.00	2.40
.014	1.45	2.17	5.28	1.17	.95	2.55	1.64	2.17
.10	1.98	1.23	3.98	.62	1.08	2.28	1.26	1.78
1.0	1.95	1.65	3.00	.42	.61	2.48	.91	1.57
4 3	1.55	1.03	2.14	.67	.74	1.21	.59	1.13
i7 1	1.57	.97	3.41	.58	.95	1.57	1.08	1.45
				125 CPS				
.004	1.13	1.06	3.45	.93	1.69	1.53	2.01	1.69
.014	1.43	.94	4.28	.65	.77	1.73	1.67	1.64
.10	1.00	.89	2.39	.60	.56	1.62	1.71	1.25
1.0	1.17	.57	2.74	.48	.58	1.92	1.18	1.23
4 3	1.20	.83	2.62	.63	.70	1.04	1.52	1.22
l7 1	1.48	.82	2.75	.83	1.07	.76	1.38	1.30
				6000 CPS				
004	.90	.77	4.43	.47	1.49	1.52	2.65	1.75
014	1.40	.77	4.67	.43	1.30	2.32	1.10	1.71
.10	1.52	.54	4.46	.30	1.08	1.61	1.08	1.51
1 0	1.73	.67	3.92	.43	1.03	1.54	1.94	1.61
4.3	.83	.79	3.95	.37	.59	.97	.42	1.13
l7.1	.45	.82	4.21	.45	.79	.67	.88	1.18

This procedure was followed for 1000 cps at SLs of 5, 10, 20, 40, 60, and 80 db. In addition, data were collected at 125 and 6000 cps at six loudness levels matched individually (by monaural alternate balance technique) with the six SLs of 1000 cps.

Results and Discussion

See Table 2 and Figure 2. We prove with these data:

1. that it is the 'forced' nature of the choice which results in the excellent $DLs_{75\%}$ at *weak* loudnesses by the method of right and wrong cases in Experiment I. In Experiment II, where the stimulus *but not the judgment* is comparable to Experiment I, the mean JND rises to 2.4 db; and we show

2. that it is the stimulus conditions in the experiments of the Knudsen-Riesz type which result in their excellent JNDs at the *high* loudnesses; note that in Experiment II the judgmental situation is quite comparable to Knudsen-Riesz, *but the stimulus conditions are not;* and note that in Experiment II the mean JND is never less than 1 db, while the JNDs of Knudsen-Riesz are commonly around 0.5 db.

We are led to conclude, among other things, either that the Knudsen-Riesz type of stimulus condition is a different sort of auditory task than the inter-
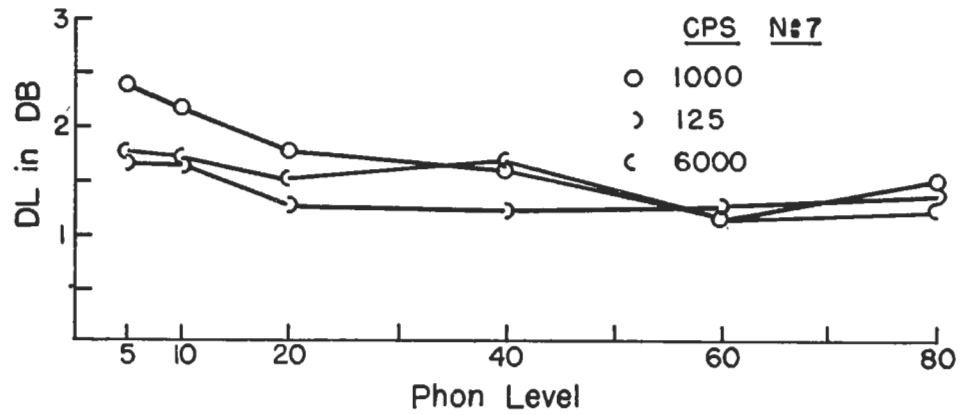
FIGURE 2. Mean JND in db for Loudness-Memory, method of limits-adjustments.

rupted-stimulus task, or else that the Ss we used were inherently different from Riesz's, both as to average JND and as to effect of overall loudness. To check the latter point, we performed another control experiment.

Experiment III: A Repetition of Riesz

A General Radio Twin-Oscillator Type 1303A was modified to produce two frequencies independently controlled in voltage and beating at 3 cps as shown in a vibrating meter needle; the oscillations were continuously checked. The signal was fed to a monaural Permoflux PDR-8 phone in an MX socket. Subject, seated in a soundproof room, determined his absolute threshold by the method of adjustments for the standard voltage at 1000 cps. The E then set that voltage to the required SL, whereupon S raised the second voltage until beats could just be ascertained. He was allowed time to fluctuate around this value until he was ready to report about 50% audibility of beats. (This is our interpretation of about what Riesz required of the S.) Both voltages were then measured prior to the mixer circuitry.

Six experienced Ss made at least six independent judgments each for every SL: 5, 10, 20, 30, 40, 60, and 80 db.

Results and Discussion

The data are entered in Table 3. All Ss showed a steady improvement in sensitivity from 5 through 80 db SL. Figure 3 shows a close correspondence between our data and those of Riesz for the same set of conditions. We are thus assured that no especial effect of subject selection is operating in our Ss.

Churcher, King, and Davies (10) accomplished a sine-wave transition at 0.8 - 1.5 cps between two intensity levels; S was required to judge when a steady tone acquired a modulated character. These data do not differ in essentials from earlier or later work on sine-wave amplitude modulation.

It has been suggested by Oldfield (66) that the loudness-modulation ΔI could most quickly be estimated from a recording of the tracking behavior of S as he controls a motor-driven attenuator to make more or less detectable the modulation of a tone. In this way one could conveniently study momentary fluctuations of differential sensitivity. (A partial automation for collecting ΔI in loudness-memory has similarly been suggested (45).)

A subquestion arose, whether a true sine-wave amplitude modulation would be affected by overall loudness in the

TABLE 3. JND in decibels, Loudness-Modulation after method of Riesz. Data at 100 cps.

Sensation Level	Subjects						
	JDH	JJO	CKM	CEW	CEG	ARJ	Mean
5	3.01	2.79	4.73	1.76	1.76	3.07	2.85
10	2.17	3.47	1.87	1.07	1.85	3.03	2.24
20	1.76	2.50	1.24	.64	1.43	2.30	1.64
30	.61	1.40	1.30	.61	1.21	1.75	1.14
40	.58	.94	1.30	.61	.97	.61	.83
60	.36	.30	.92	.21	.75	.42	.49
80	.35	.23	.68	.21	.38	.52	.39

13
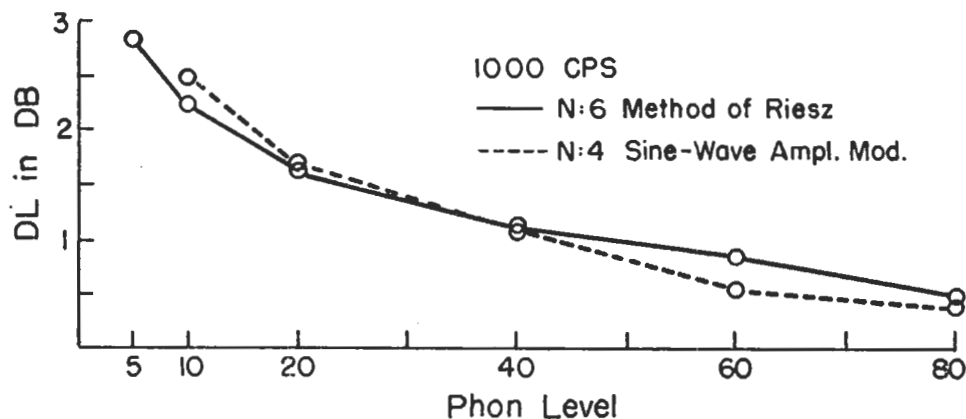
FIGURE 3. Mean JND in db for Loudness-Modulation.

same way as Figure 3 shows the frequency-beat type of stimulus to be. Accordingly we derived $DL_{75\%}$ for four Ss by a forced choice '1' vs. '2' judgment at a selection of loudnesses; these data too are entered in Figure 3. It is clear that both types of amplitude modulation are similarly affected by overall loudness, regardless of the type of judgment employed.

Rate of Modulation

It would take us too far afield fully to consider the effect of rate of modulation, but the results of Zwicker (*94*) should be cited and especially his book with Feldtkeller (*20*) read by the care-ful student. Their results with pure tones, with white noise, and with bands of noise are now well-known (Ebel (*18*) added information on spoken and sung speech and on piano and orchestral music in a study on the distortion factor of loudspeakers). More recently Stott and Axon (*87*) corroborated the German work using pure tones, piano music, and white noise. They found for pure tones that (at 75 phons) a modulation rate of 50 cps was somewhat the more difficult rate, and 2.5 the least. Considering even the more difficult rates these data show that the human ear is sensitive to a 2 - 4% amplitude modulation over a major portion of the auditory area.

Experiment IV: A Preliminary Loudness Matrix

At this point, in view of differences among our sets of data, it became imperative to know more about the interrelationships among tests of loudness discrimination.

An early question to which we addressed ourselves was whether the area of loudness discrimination was in fact a closely spaced domain such that all tests ostensibly of the ΔI were equally meaningful. We had intimations that this might not be the case:

1. Karlin (46) was able to discover only a poorly-defined loudness discrimination factor, which moreover was closely allied to a time discrimination factor;

2. the Seashore loudness test did not correlate very highly with the Harvard Test No. 7, Loudness Discrimination for Bands of Noise (47);

3. Dimmick and Olson's $DLs_{75\%}$ were so far removed from any other set of data that it was clear a unique factor (not necessarily of loudness, but possibly so) was operating in their work;

4. the Riesz experiment, generally agreed then to yield the best ΔI sample, had alliances with frequency as well as intensity, and was in all probability factorially complex; and finally

5. some preliminary work we had done with tests of ΔI, masking, and contact detection had led us (36) to reconsider the unity of the ΔI domain as Seashore had left it.

To explore these possibilities, we took the opportunity to include six tests of ΔI in a matrix of 12 other tests, four of masking and contact detection and eight of pitch discrimination, with which we were concerned for reasons irrelevant to this paper.

Results and Discussion

This experiment has been described in detail (65). The 18 tests were administered twice to each of 92 men in groups of up to 25. A summary of this material for the immediate purpose is contained in Table 4, which shows the ranges and averaged r's within and also among categories. (The averages are not of course to be considered as any estimate of central tendency.)

Note that the average r among the six tests of ΔI was no higher than the average r between all the ΔF and ΔI tests! Some, but not all, of this finding arises from the fact that with the same test-length a test of ΔF can be made to yield a higher test-retest r than a test of ΔI.

The reader is next invited to inspect Table 5, the r's within the ΔI category alone. It was already clear from Table 4 that the ΔI area cannot be a unitary, tightly coherent domain with all samples of ΔI grouping strongly. A closer look at the whole 18-test matrix, and consequently at the ΔI tests, however, is provided with the technique of vector geometry (30); a centroid factor analysis yielded five oblique identifiable factors, the first two concerned exclusively with ΔF. The third factor to emerge was a ΔI grouping as follows:

TABLE 4. Average product-moment correlations and ranges within and among some auditory areas.

	Pitch	*Loudness*	*Complex Signal Detection*
Pitch (8 tests)	.44 (.21 to .73)		
Loudness (6 tests)	.27 (.07 to .47)	.28 (.15 to .37)	
Complex Signal Detection (4 tests)	.26 (.0 to .5)	.23 (.04 to .48)	.18 (.0 to .35)

	Loading
MRL: $DL_{75\%}$ for tone spurts 0.15 sec long at 1 kc masked by wide-band noise	.46
Harvard: Loudness Discrimination for Bands of Noise	.42
Harvard: Sentences in Noise	.23
Seashore: $DL_{75\%}$ for Loudness	.23
MRL: $DL_{50\%}$ for tone spurts 0.5 sec long at 1 kc masked by wide-band noise	.215

Note that a wide variety of tests, including those of contact detection, exhibit significant loadings; it can provisionally be characterized as a Loudness/Detection, or Loudness/Masking, factor.

The fourth factor to emerge was as follows:

	Loading
MRL: Masked propeller noise, $DL_{50\%}$	.43
Harvard: Pitch Discrimination for Bands of Noise, $DL_{75\%}$	.42
MRL: $DL_{75\%}$ at 250 cps	.39
Intelligence	.33

TABLE 5. Intercorrelations among tests of ΔI.

Tests	*2*	*3*	*4*	*5*	*6*
1 Seashore Loudness Test	.35	.27	.24	.28	.33
2 MRL: $DL_{75\%}$ at 250 cps		.33	.17	.32	.15
3 MRL: $DL_{75\%}$ at 1 kc			.33	.37	.32
4 MRL: $DL_{75\%}$ for increments of .15 sec duration at 1 kc				.27	.29
5 Harvard: $DL_{75\%}$ for noise bands					.19
6 MRL: Forced-choice variant of Riesz Test at 1 kc					

This can only be regarded as a complex auditory discrimination factor too diffuse to name.

The fifth factor to emerge was as follows:

	Loading
MRL: $DL_{75\%}$ for 1 kc	.43
MRL: $DL_{75\%}$ for increments 0.15 sec long in a 2 sec. tone at 1 kc	.39
MRL: Repetition of Riesz at 1 kc	.29

We seem to be looking here at a pure tone loudness factor, but on the other hand the other two tests of the pure tone ΔI do not show, namely, the Seashore and the MRL $DL_{75\%}$ at 250 cps.

This experiment led us reluctantly to conclude that the next step in our thinking could be taken only after mounting a full-scale attack using a much larger matrix of samples of ΔI. Accordingly, we undertook such a study.

Experiment V: The Loudness Discrimination Area

Seventeen tests of the ΔI were impressed on tape or disc and administered to 112 young men. Inasmuch as this material has not been reported as yet, some space will be given to it here.

Tests

(A). 1000 cps. Paired tones each 1 sec in duration, interstimulus of 0.3 sec, judgment interval 4.0 sec. Subject judges second tone 'louder' or 'softer.' Five items at 3 db difference, 5 at 2 db, 15 at 1.5 db, 15 at 1.0 db, 15 at 0.7 db, and 5 at 0.4 db.

(B). Same as (A) exactly except interstimulus interval was 3.0 sec.

(C). Same as (B) exactly except frequency was 250 cps.

(D). Same as (A) exactly except frequency was 250 cps.

(E). 1000 cps. Pairs of tones each 2.5 sec in duration, interstimulus interval of 0.25 sec, judgment interval 4.0 sec. One of the pair is amplitude-modulated at the rate of 3/sec with a sine-wave pattern, the circuit taken from Brogan (4). Subject judges whether tone '1' or '2' has the modulation quality. Ten items at 4.4 db peak-to-peak, 10 at 3.6 db, 20 at 3.0 db, 20 at 2.5 db, 20 at 1.8 db, and 20 at 1.4 db.

(F). Same as (E) exactly except frequency was 250 cps.

(G). 1000 cps. Pairs of tones each 0.75 sec in duration, interstimulus interval of 0.75 sec, judgment interval 4.0 sec. Subject judges second tone 'louder' or 'softer.' Ten items at 3.5 db, 10 at 2 db, 20 at 1.7 db, 20 at 1.1 db, 20 at 0.8 db and 20 at 0.4 db.

(H). Same as (G) exactly except that noise-bursts were used instead of pure tones. Noise-bursts were produced by passing a square wave train at 100/sec through a 1000 cps high-pass filter.

(I). Same as (H) exactly except a 1000 cps low-pass filter was used.

(J). Same as (H) exactly except that a band of white noise fed through a 500 - 2000 cps bandpass filter was used.

(K). 1000 cps. Pairs of tones each 2.5 sec in duration, interstimulus interval of 0.75 sec, judgment interval 4.0 sec. One of the pair contains beats at 3/sec produced by increasing the intensity of a 1003 cps tone until beats are audible, after the manner of Riesz. Subject judges whether tone '1' or '2' has the beat quality. Twenty items at 2.2 db calculated from Riesz's formula, 20 at 1.5 db, 20 at 1.25 db, 20 at 0.9 db, 20 at 0.7 db and 20 at 0.5 db.

(L). 1000 cps. Pairs of tones each 3.0 sec in duration, interstimulus interval of 0.75 sec, judgment interval 4.0 sec. One of the pair contains an in-phase increment of intensity 0.75 sec in duration, rise-fall time of 0.01 sec. Subject judges whether tone '1' or '2' has the increment. Twenty items at 3 db, 20 at 2 db, 20 at 1.6 db, 20 at 1.2 db, and 20 at 0.8 db.

(M). Same as (L) exactly except tones were 1.5 sec and the increment 0.15 sec in duration.

(N). Same as (M) exactly except the input to the switch was a square-wave train at 100/sec.

(O). Same as (M) exactly except the input to the switch was a white

noise fed through a 500 - 2000 cps band-pass filter.

(P). Harvard Test No. 7, Loudness Discrimination for Bands of Noise.

(Q). Seashore Loudness Test, Series B.

(R). IQ.

Subjects

Young men of average intelligence or higher, with normal audiograms at least from 250 - 2000 cps, served as Ss. They were motivated by indirection (avoiding more onerous tasks around the reservation) and by giving them the unexpected pleasure of being treated as gentlemen.

Conditions of Testing

Men were tested in groups of 25 or less by means of matched monaural PDR-8 phones in MX/41-AR cushions. Intensity of all test items was set at 40 db SL for a S with '0' hearing loss at 1000 cps by audiometer.

Each test had impressed on it full instructions and easy examples. Items were numbered, individually or in blocks of 10, so that S could hardly lose his place in a series. Opportunity was given for questions, additional examples, or fuller instructions until all Ss were willing to start the test. Test-order was randomized so far as possible among the half-dozen groups of men.

Phychometric functions were drawn on graph paper as the data came in; by this means we could check on the internal consistency of each S on each test. For some Ss, some of the tests were too difficult and the first few easy levels were again administered, the total

per cent correct again being graphed. For the first four tests, of only 60 items each, many of the men had to receive several full administrations before a psychometric curve was accepted. It had previously been determined that the stimulus pattern used in most of the other tests had an odd-even reliability of about .9, and a test-retest reliability of .7 - .85 under the conditions and with the Ss we typically used.

When a psychometric function using all available data was accepted, it was graphed and the 75% point picked off and used as the estimate of $DL_{75\%}$ for that S for that test.

Two sorts of compromise were accepted:

1. Certain Ss with relatively very poor sensitivity were not clearly sampled on some tests, and the $DL_{75\%}$ contained more than average error variance. In these cases the DLs were nevertheless included, in the expectation that the 'stanine' treatment given the test distributions (described below) would minimize the error—as indeed proved to be the case.

2. Four men missed two tests altogether, and there were omissions of one man on tests L and N, two men on tests G, I, and K, three men on test P, and four men on test M. In these cases the man was assigned a ΔI at the median of the test distribution, so that results would not at all influence the r's for that test.

Results

The intercorrelation matrix was not based upon the raw distributions but on distributions normalized in stanines, whereby the ΔIs for any test are placed

TABLE 6. Product-moment correlations for Experiment V (decimals omitted). See text for descriptions of tests.

Test	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R
A	66	52	66	47	50	32	47	42	29	38	36	19	38	38	35	39	57	14
B		67	47	39	48	40	41	58	45	46	45	21	45	50	40	48	59	16
C			66	54	45	30	46	38	30	41	24	15	30	37	24	32	51	23
D				50	35	35	39	20	16	24	28	15	25	32	24	38	51	18
E					73	40	36	45	14	34	53	17	44	44	41	31	31	15
F						66	24	35	16	19	37	22	22	39	33	22	30	14
G							77	30	39	45	26	30	39	46	46	32	40	17
H								74	35	47	39	32	40	43	31	39	41	06
I									69	41	24	26	36	49	23	39	40	01
J										75	34	35	56	45	46	41	47	15
K											88	32	51	51	38	21	37	16
L												71	53	36	37	22	20	−02
M													88	49	52	40	42	06
N														80	42	33	47	30
O															56	33	31	11
P																82	48	06
Q																	88	29
R																		90

in nine categories, the categories being chosen to encompass the midscores in category 5, with the extremes in categories 1 and 9. This is common statistical practice and has several advantages beyond IBM convenience. In our case, it has the effect of reducing the importance of the error involved in estimating the ΔI for an especially poor S; whatever the 'true' ΔI may be, he is still in category 9.

The matrix (Pearson r) is shown in

TABLE 7. Unrotated factor matrix for Experiment V (decimals omitted).

Test	F_1	F_2	F_3	F_4	F_5	F_6	F_7	h^2
A	695	308	152	155	120	094	189	683
B	745	102	—100	—225	155	—123	070	670
C	652	369	208	097	—129	097	189	676
D	553	404	171	175	—156	—074	—171	588
E	632	093	—314	243	202	116	163	646
F	494	116	—311	107	—118	—210	—050	426
G	626	—050	162	087	—177	121	009	474
H	628	—060	—128	—149	153	—161	182	519
I	515	—210	204	—311	—106	—105	211	514
J	664	—248	163	—115	114	148	—048	579
K	598	—095	—326	102	083	043	056	495
L	449	—450	087	209	—064	—165	—091	495
M	675	—380	076	139	233	086	—063	691
N	708	—166	—156	—124	—279	114	059	663
O	591	—212	—062	183	052	042	—241	494
P	566	059	207	—164	159	—188	—139	474
Q	710	235	176	—243	036	071	—125	671
R	249	159	—139	—107	—194	341	—171	301

TABLE 8. Rotated factor matrix for Experiment V (decimals omitted).

Test	V_1	V_2	V_3	V_4	V_5	V_6	V_7
A	—056	510	124	004	120	—119	—155
B	—019	306	116	—228	014	—142	290
C	—047	536	028	—018	—059	032	—219
D	—068	536	—008	274	—186	001	034
E	—056	053	523	003	217	—032	—032
F	—083	058	361	054	—230	005	216
G	326	226	—027	098	—066	095	—137
H	047	150	175	—259	—011	—199	199
I	307	192	—217	—323	—168	—093	032
J	441	163	—125	—010	167	—034	053
K	106	—076	410	—020	088	024	094
L	519	—058	—024	226	—170	—171	032
M	501	046	065	157	212	—171	034
N	330	—030	140	—134	—130	266	016
O	364	017	141	290	061	—009	130
P	106	435	—188	009	—032	—254	295
Q	069	502	—176	—048	055	026	191
R	037	—003	045	040	099	446	001

Table 6 and may be studied profitably by the reader from more points of view than we will take time to note here. Test-retest r's are included.

In the first place, where so many pairs of tests, alike in all but one detail, such as frequency or interstimulus interval, yield r's in the .50's and .60's, it may be taken that our goal of a minimum .7 test-retest was commonly reached. In the second place, this matrix confirms in many details that of Experiment IV and extends it until a nearly final picture of the ΔI emerges.

The unrotated factor matrix is included here as Table 7 for completeness, and the final rotated matrix is presented in Table 8. From Table 8 we abstract Table 9, which gives significant loadings on the first three factors after three oblique rotations. The remaining four factors of Table 8 have negligible loadings.

The first factor to emerge is an old

TABLE 9. Factor loadings for the first three factors in Experiment V (decimals omitted).

	Factor 1		Factor 2		Factor 3
Test	Loading	Test	Loading	Test	Loading
L	519	C	536	E	523
M	501	D	536	K	410
J	441	A	510	F	361
O	364	Q	502		
G	326	P	435		
N	330	B	306		
I	307				
Loudness/Masking		Loudness-Memory		Loudness-Modulation	

acquaintance, a broad loudness factor which includes tones, noise, and clicks, by both increments and by paired stimuli. Note, however, that only one of the five tests of $DL_{75\%}$ by *paired pure tones* comes up, and *none* of the three modulation tests. Note that five of the six incremental tests and three out of four of the noise tests *do* come up. Our thinking on this factor is hereby sharpened very considerably. It is not a generalized ΔI factor: it certainly excludes modulation and practically excludes pure tones by paired stimuli. It does include any ΔI for noise or ΔI by increments for either noise or pure tones.

To extend our thinking on this factor, the reader is invited to return to the third factor of Experiment IV, showing without any real question the same factor arising from somewhat different tests. Note that the third factor as defined in the limited-range matrix of Experiment IV is concerned in three of four tests with noise-masking—either noise-in-noise or tone-in-noise. (Incidentally, it is not by chance that the Riesz modulation test did *not* show on this factor.)

As a result of this line of reasoning, in which an incremental test, whether of tones, white noise, or clicks, is thought of as a masking test (see especially Miller (*60*)), we wish to refer to this grouping as a Loudness/Masking Factor, and we predict for the future that any test using noise, or offering immediately adjacent intensity levels either of tone or noise for judgment, will show positive loading on this factor. Our best estimate for 'tag' tests would be tests L, M, and O.

The second grouping offers four tests, all very similar, and all featuring pairs of pure tones. Since other tests involving interstimulus intervals *but not pure tones* are *not* found in this area, we conclude that the memory itself is not the only salient feature, but the critical features are a combination of memory plus a pure tone stimulus. Accordingly we term this the Pure Tone Loudness-Memory Factor. It is adequately sampled by Test C as a 'tag.'

The third grouping is clearly concerned exclusively with amplitude modulation, is called the Loudness-Modulation Factor, and is well sampled with the recommended Test E. The remaining four factors have such low loadings as to be uninterpretable.

Discussion

The success of dividing the ΔI area into three factors has both practical and theoretical consequences. We can now begin to search for different ways in which the factors separate themselves both in normal-hearing ears and in the partially deafened. In the normal ear we can expect to observe differences in the way the index of sensitivity changes with frequency, with loudness, and perhaps with a masking background. The defective ear may, however, be far more informative as to the psycho-physio-neurological natures of the auditory tasks. It might, conceivably, be possible that an hypacusic ear be defective or show an anomalous effect of SL on a standard Loudness-Modulation test but not on standard tests of Pure Tone Loudness-Memory or of Loudness/Masking; or a variety of patterns could occur in consequence of particular diagnoses. In this case a happy reciprocity could occur:

a. the pattern of test results could assist in otological diagnosis, and/or

b. the lesion in certain structures or tissues which yielded a particular profile on factorially pure tests could help to elucidate the essential operations of the auditory system in handling such inputs.

As a matter of fact, the use of ΔI tests in the otological clinic is now several years old, spurred on by a search for a good monaural test of recruitment; and it becomes necessary at this time to digress, unfortunately at some length, in order to attempt an integration of this material.

The Present Status of the ΔI
in the Oto-audiological Clinic

When the conception became current as a result of the work of Pohlman and Kranz (72) and especially of Fowler (24, 25) that a loudness of several hundred thousand millisones could be crowded into an intensity range of perhaps only 60 db in some partially deafened ears as contrasted with perhaps 120 db in the normal ear (that is, recruitment), the obvious corollary was that in such an ear each decibel of intensity should encompass more millisones than normally, and loudness discrimination should improve. Early general proposals to this effect were made by Brinitzer (3), Reger (79), and de Maré (12).

Lüscher and Zwislocki (56, 57, 58) first succeeded in using a ΔI for intensity modulation as a clinical index of recruitment. They connected an amplitude-modulation circuit to an amplifier to produce continuous variations in voltage output. Differential thresholds were reported in percentage modulation, actually the percentage decrease from the peak modulated carrier voltage, or $\% = E/E_{max}$. A series of papers has subsequently appeared from Lüscher's laboratory (52, 53, 54, 55, 59, 64, 71).

Lüscher and Ermanni (55) give percentage modulation JNDs at 40 db sensation level on one case of tubostenosis, three cases of acute and five of chronic middle ear disorder, and six cases of otosclerosis. While it is true

that data on loudness-balancing were not given as a direct indication of recruitment or its absence, there is a good presumption that in such cases recruitment, if present, is at least not quick and complete. Six otosclerotics had a mixed deafness and presumably showed some recruitment. Their average JND was 7-9% for all the frequencies 125, 250, 500, 1000, 2000, 3000, 4000, 6000, 8000 cps. For the other nine defective patients the average JND was somewhat larger, from 8-14% at all nine frequencies, the value most usually being 10-12%.

On the other hand, in 14 patients with acoustic trauma, the average JNDs through the frequencies most affected were appreciably smaller, being 10%, 9%, 7%, 6%, 6%, and 8% at 1, 2, 3, 4, 6, and 8 kc respectively. In these cases there is no real doubt that an improvement in intensive sensitivity to amplitude modulation occurred in a frequency region exhibiting quick recruitment. There were also nine cases of endogenous perceptive deafness, with especially acute average JNDs of 8, 7, 5, 5, 6, 6, and 8% for the frequencies 500-8000 cps in order.

Together with other supporting cases, these data are convincing to the writer that, in general, the otological conditions associated with recruitment may also be associated with improved sensitivity for amplitude modulation.

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Other Evidence

Somewhat more direct evidence is provided by Neuberger (*64*), who took amplitude-modulation JNDs at several intensity steps on patients demonstrated to have sharply recruiting ears. The JND was always superior to that in the other, normal, ear at equal loudness. Also, on two patients with nonrecruiting deafness the JND never was less than 10% at 1000 cps from 10 through 60 db SL. In all, 14 patients with diagnosis (in the main) of acoustic trauma (a well-known recruiting type) were tested at 10, 20, 30, 40, and 50 db SL, at from one to four frequencies. Of these 14 patients, 12 gave JNDs of 2-6% at all frequencies tested at 40 db

SL, thus corroborating the conclusion of Lüscher and Ermanni that perceptive deafnesses yield exceptionally good sensitivity at 40 db. Complete loudness-balancing data is given on these patients at all frequencies examined. It is perfectly clear that in those patients with recruitment, the amplitude-modulation JND reaches at 40 db SL uniformly a very sensitive value, while in two patients who show little or no recruitment, the JND never is improved below 10-12%. Figure 4, taken from Neuberger's Tables 1 and 2, shows the case for two typical patients with quick recruitment, Patients 2 and 6, and the two patients without recruitment, Patients 13 and 14.
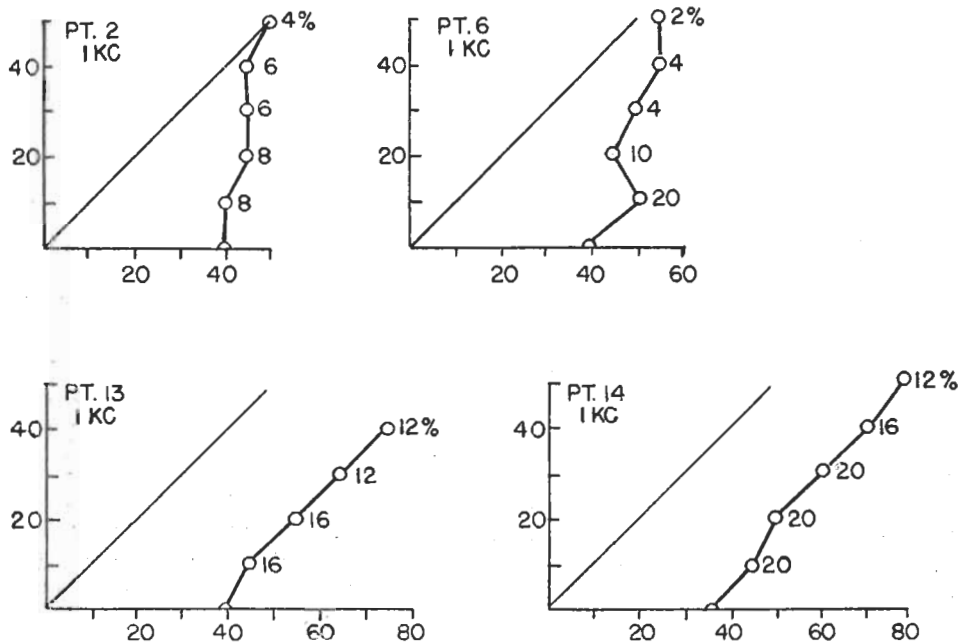
Figure 4. Shows JND for Loudness-Modulation improving markedly with increasing loudness in recruiting ears, but improving relatively little in nonrecruiting ears (data from Neuberger, *64*). The abscissae express db over threshold on good ear, data for worse ear. The ordinates express db over threshold on good ear, data for good ear. An open circle represents the point of loudness-balance between ears. The numbers beside the open circles give the threshold of amplitude-modulation in percentage in worse ear.

A glance at the JNDs for these 14 patients reveals that without exception the JND tends to improve as overall intensity is raised. This is of course in line with data on the normal ear.

Doerfler (*16*), in his dissertation under Carhart, was very early in connecting improved ΔI with perception deafness, and presumably, with recruitment. His data by the Riesz amplitude-modulation technique clearly categorized the perceptively deaf as a hypersensitive group. It should be pointed out that Doerfler found sensitivity at 10-30 db SL to distinguish perceptively deaf ears better than the 40 db level recommended by Lüscher.

Denes and Naunton (*13*), apparently independently of Lüscher, reasoned that the change in the intensive JND as loudness increased, would differ in the recruiting ear from that in the normal ear. In the normal ear as loudness increases, the JND improves; Denes and Naunton felt that in a recruiting ear the sensitivity would be found best at *weak* sensation levels and would deteriorate at *louder* levels. They described eight such patients who demonstrated this effect by the Loudness-Memory method; but conversely an *improvement* of sensitivity was found as intensity was raised 10, 30, and 50 db above threshold in six normal persons, as well as in three patients with conductive impairment and demonstrated lack of recruitment, plus three more patients with otosclerosis with presumed lack of recruitment but in whom loudness balancing could not be attempted.

Improved Technique

In a later paper Denes and Naunton (*14*) took note of Lüscher and Zwislocki's work and pointed out that sinusoidal modulation introduces sidebands such that the patient is asked to judge not only on the basis of cues for loudness, but also on the basis of cues for pitch and 'quality.' They described again their own test using the method of limits but with paired tone durations at 4 and 44 db SL. A *deterioration* of sensitivity from 4 to 44 db was to be taken as evidence for recruitment, whereas an *improvement* was to be taken as normal or at least as evincing no recruitment.

A real advance in technique was made by Denes and Naunton when they abandoned the attempt to relate an individual's JND to that of a group of 'normal' ears or a group of 'recruiting' ears and developed the procedure of each ear serving as its own control. Too many 'normal' ears have very acute discrimination and too many 'recruiting' ears have inherently poor discrimination to draw a clear dichotomy. But by comparing an individual ear's performance under two conditions, one avoids depending upon absolute values and eliminates one important source of variance.

In Denes and Naunton's method a first tone was presented for 1.7 seconds; a silent interval of 0.33 seconds intervened, then a second tone of 1.7 seconds at a higher intensity. Buildup and decay of the tones was 0.08 seconds. Patient judged when the second tone became louder (or, in another series, softer). About 5-10 minutes were allotted to finding the mean JND at each of the two SLs. Tests were run on 23 patients showing recruitment and on 20 normals or nonrecruiting ears. All of a group of 20 nonrecruiting ears improved as loudness was raised, whereas 20 of 23 recruiting ears either deteriorated or

remained with no change from 4 to 44 db SL. Of the three anomalous cases, two were probably influenced by cross-conduction. There is little doubt here that the recruiting ears were behaving differently from nonrecruiting ears and that the contention of Denes and Naunton is correct that in a rapidly-recruiting intensity region (that is, near absolute threshold), JNDs *by the Loudness-Memory technique* are better—enough better to cancel partially (or even completely) the normal tendency for ΔI to be *worse* near absolute threshold. These data show the wide individual variation which makes so valuable the technique of using an ear as a self-control.

A divergence exists between the work of these authors and the data reported from Lüscher's clinic, as to whether sensitivity improves or deteriorates as the stimulus is changed from weak to louder intensities. The results described above have been reported in such detail in order to make it clear that tests of ΔI by Loudness-Memory and by Loudness-Modulation *both* are applicable to the pathological ear and can both be used to assist in diagnosis. Rather heavy criticisms of each method have been made by the other school on the basis that amplitude modulation produces side-bands to blur the 'quality' of the tone or that the loudness-memory yields an incongruously poor sensitivity at higher intensities, but it seems to the writer that such criticisms are beside the point. It is furthermore not necessary to survey the several inconclusive reports and the several apparently contradictory reports, throw one's hands up, and simply await the appearance of further inconclusive and inconsistent reports.

Resolution of the Conflict

What the present paper of course shows is that in Loudness-Memory and in Loudness-Modulation we are not dealing with the same psychoacoustic trait at all. In Loudness-Modulation we are dealing with a trait which is probably rendered considerably more acute by whatever otological conditions cause recruitment, and this improvement in sensitivity exists at about equal strength over the whole range of sensation level. On the other hand, in Loudness-Memory we are dealing with a trait which is also by a recruiting-type lesion rendered considerably more acute, *but only in the intensity region of rapid recruitment*. It would seem clear that a particular type of otological pathology may affect one trait in one way and the other trait in a quite different way.

With this thought in mind we are better able to assess the several reports which have appeared since the original validating papers. Pirodda (*71*) from Lüscher's clinic showed that the improvement in amplitude-modulation JND existed in nine perceptively-deaf ears as well for bone-conducted sound as for air-conducted, the percentage modulation thresholds being 6-8.5% at the higher frequencies for these subjects by bone, as against 14.8-17.6% for three middle ear deafnesses and 12-14% for three normal ears. Thus, Pirodda confirms earlier work and adds the logically valuable though foregone conclusions that any change in sensitivity to amplitude-modulation must be a direct consequence of lesion centrad to the middle ear.

Lüscher (*52*) notes that a psychogenic deafness may show an exaggerated poor sensitivity, while Greiner *et al.*

(29), in a verified true nerve deafness, find also that sensitivity is diminished. On the other hand, Lidén and Nilsson (50), Lund-Iversen (51), and Zollner and Hahlbrook (93) present data showing that the individual variability in normal and partially-deafened ears is enough to make it difficult to use amplitude-modulation for individual diagnosis. One would not wish to categorize an ear as 'recruiting' on the basis simply of good musical talent, of course; for example, using Lüscher's technique, Lidén and Nilsson found an average threshold of 6-8% at six frequencies for young normal adults, and they found some individuals who yielded thresholds consistently lower than 6%. Lüscher's criteria would categorize these clinically normal ears as 'recruiting' on the basis simply of extra-ordinarily acute musical talent.

The writer has no wish to enter this controversy through the medium of this paper, except to offer gratuitous advice that the principle of self-control could be added to Lüscher's method by adding other sensation levels to the 40 db recommended.

Jerger (41) used Lüscher's technique with 15 patients with pure conductive deafness and 74 with sensori-neural involvement. Clinical diagnosis was made for the most part by Dr. G. E. Shambaugh, Jr., Department of Otolaryngology, Northwestern University Medical School. On the basis of his and Doerfler's previous experience with such a test, Jerger reduced the testing intensity to 15 db sensation level, used only the movement from no-modulation to modulation for the patient to judge, and avoided abrupt interruption of the stimulus.

Jerger's results amply confirm in detail those of Lüscher's clinic. No case of conductive deafness exhibited a percentage modulation less than the mean data of 39 normal-hearing ears minus two standard deviations. On the other hand, 53 of the 74 patients with sensori-neural involvement *did* show more sensitive thresholds than the mean-minus-two S.D. criterion; it is equally significant that in the remaining 19 sensori-neural patients, the diagnosis was confined to presbyacusis, streptomycin, psychogenic overlay, brain or nerve involvement, and one case of malingering—just the etiologies stated by Lüscher to exhibit no specially sensitive threshold.

Jerger (42) subsequently abandoned testing at the single sensation level of 15 db in favor of computing the difference in sensitivity between 10 and 40 db SL. He thus combines (a) the essential stimulus conditions of Lüscher's technique plus the principle of self-control and (b) the reasoning of Denes and Naunton that recruitment should most affect sensitivity where recruitment is most rapid, near threshold. Particularly convincing is his table showing that (in a group of patients with deafness of cochlear origin) the sensitivity difference between the SLs of 10 and 40 db is greatest for 75 patients with no bone conduction loss (0.95 db difference between sensitivity data at 10-40 db SL) and that this difference of 0.95 db *progressively and regularly* decreases to 0.10 db difference on the average with 15 patients with bone conduction loss averaging 30 db. In Jerger's data the more the bone conduction loss, the less difference there was between the DLs for 10 and for 40 db SL. This test is said to work well

in the clinic, and several convincing case histories are presented.

A study by Carhart and Lightfoot (6), using amplitude-modulation on normal and impaired ears in quiet and in the presence of background noise, should be cited here for completeness, but since the study was directed to a practical question of communications rather than to a clinical or theoretical hypothesis, the data have limited value for our special purpose here. However, from their data can be abstracted the information that, although the sensitivity at either 15 or 30 db SL was not reliably different between 31 normal ears and 16 ears with a variety of unspecified sensori-neural involvement, nevertheless the *difference* in sensitivity as between the 15 db and 30 db sensation levels was always, and reliably, *less* for the 16 impaired ears than for the normals. This is in the direction predicted by Jerger.

Hirsh, Palva, and Goodman (39) survey the problem through 1954, laying particular stress on the differences which appear among the studies. They conclude, 'There may be some relation between the size of the DL under certain procedures and the presence of recruitment, but . . . whatever relation may exist is so dependent on features of the procedure that a single DL technique cannot yet be recommended for general clinical use.' They used a variant of the constants method, the patient judging whether two discrete tones were different or same in loudness. Data for both 'Descending' and 'Ascending' methods are presented. Fairly complete data were given at 5, 25, and 40 db SLs for 22 ears showing recruitment and 11 ears not showing

recruitment, together with diagnosis (eight uncertain).

On comparing their own data by Loudness-Memory for normal vs. patients either with or without recruitment, Hirch *et al.* concluded that measures of intensity DL were almost useless in identifying recruiting-type ears, because of the overlap among their groups. Now the overlap among groups is a fairly consistent finding in psycho-acoustics as applied to audiology and should distress no one. It is therefore a little suprising that these workers did not take the opportunity to go beyond the absolute values of their DLs. Let us look at the *change of sensitivity within each patient* as sensation level was changed from 5 through 40 db. The number of patients in each of their sub-groups is a little scant to make definitive statements, but it seems that the five otosclerotics show less improvement, as loudness increases, than either 18 normals or eight Ménière's patients on whom full data were obtained, or especially on the five cases of true nerve deafness. Amplifying and extending data of this sort, on larger groups and with more varied etiologies, should eventually show whether the technique of Hirsh *et al.* has a useful application in the clinic. At present one reserves judgment, except to agree that changes in ΔI by the Loudness-Memory method may not always appear *pari passu* with recruitment.

On the other hand, Jerger with the 'quantal' method (43, 44) shows a reliable and clear difference between intensity sensitivity for normal and for recruiting ears, both at 10 and at 40 db SL. At regular or irregular intervals of several seconds he added an increase of intensity to a continuous tone. His re-

sults show convincingly that sensitivity in normal ears by this method is only about half as acute as in recruiting ears (ΔI of 1.81 for normal vs. 0.99 db for recruiting ears at 10 db SL, and of 1.05 for normal vs. 0.46 db for recruiting ears at 40 db SL).

Obviously still a third test, sampling our Loudness/Masking Factor, may be of clinical importance.

Summary

Several summary comments may be made on aspects of such data as are abstracted in this clinical section:

1. Slight differences in duration of stimuli, rise-fall times, intervals of silence, and so on may be pretty well disregarded, but it will not do to disregard differences in stimulus conditions involving separate primary abilities. There are three main types of ΔI which are mutually informative, not at all contradictory, and a recognition of this fact can prevent incorrect and even unfair comparisons among sets of data.

2. There is no theoretical necessity for recruitment and improvement of intensity discrimination to go hand in hand; one may appear without the other. Certain abnormal conditions in the ear may give rise both to recruitment and to improved intensive sensitivity, but certain other abnormal conditions may affect one or the other alone. For example, Lüscher, and Greiner et al. (29) have shown a deterioration in intensive sensitivity with brain damage, but we have no data at present showing that in these patients the *opposite* of recruitment was present. Thus the original enthymeme (recruitment and improved DIs often coexist,

therefore they are identical) is perhaps fallacious.

3. In the normal ear, recruitment and an improved ΔI may not coexist. Hirsh et al. have correctly pointed out that the very low frequencies climb more rapidly in loudness than the middle range frequencies (this is quite analogous to recruitment) and yet the ΔI for these low frequencies is not better but *worse* than for the middle range.

4. In the pathologically deaf ear the improved ΔI is not explained by assuming that recruitment caused the compressing of many more millisones into a relatively few db of intensity, as is commonly stated. Jerger (44) has observed that a 4000 cps tone at 10 db SL in a recruiting ear may decline nearly to 0 db SL in a minute or so due to perstimulatory adaptation, yet the ΔI may remain extraordinarily small. Here the loudness is not compressed; it is almost *lost*, without affecting the ΔI.

5. We may be pardoned here for a few strictures on the laboratory-clinic transfer. It is the experience in our laboratory that the process of collecting a reliable ΔI cannot be hurried. Many have tried to take an auditory discrimination test developed in a laboratory, shorten it drastically, and apply it under poorly controlled conditions in the clinic. We have observed that this usually yields data so erratic that one can put little trust in results. Anything like an adequate practice period is seldom provided. Some patients learn slowly, some quickly. Is it correct to make statements on a patient's hearing on the basis of his ability to adopt an unfamiliar judgmental mood? We feel enough practice

should be given, and such data continuously graphed up, until the patient approaches his asymptote. This may take up to half an hour, with sympathetic instructions, knowledge of how well he is doing, and encouragement; but unless by some means one can induce consistent judgments at near optimum, then the data for different SLs or different ears or frequencies cannot be interpreted with any confidence, and further testing time is largely wasted.

It is not sufficient to decide beforehand that all patients will receive, say, five trials moving from 'no difference' to 'just noticeably warbled,' or the like. Consistency of the data must be the criterion. Collection of data must continue, on some sort of informal sequential analysis, until E is assured that replicating all trials would not appreciably shift the average datum. For some exceptionally stable patients in the above example five trials might well suffice, but with some patients this would need to be tripled at least. Advanced statistics are not needed here, rather a distrust of blind reliance on the statistics of small samples. What is needed is a long common-sense look at the balance between the stability of any limen and the separation between it and any other limen with which a comparison is desirable. When we read, for example, that in a certain patient at 5 SL a 'descending' DL is 1.2 while an 'ascending' DL is 2.7, we wish to know at least the order of magnitude of experimental error. Is the 'descending' method really better in this patient by 1.5 db, a relatively huge difference? But at 25 db SL in that same patient the 'descending' method turns out to be 1.5 db vs. 1.0 db for the 'ascending'

method—in other words the situation is reversed and the 'descending method' seems *worse* by an appreciable amount. Have we a true reversal here? If so, the observation may be very important; but before reaching the conclusion that a valid reversal exists, the careful scientist will wish to know the extent of the several variances involved in adaptability to the experimental situation, inherent learning rate for auditory judgments, and within-observer and between-observer differences. These variances can be estimated either statistically or by common-sense scrutiny of the data plus adequate reflection on the real nature of the problem. We are not asking for an apograph of raw data but some solid indication of *repeatability* of data.

As a guide in this area, the experience of our laboratory is that with more than averagely intelligent and very well-motivated young men, something like 150 judgments of 'louder' or 'softer' must be required for a stable $DL_{75\%}$. We can shorten this somewhat if a variant of limits-adjustments can be used. However, all patients cannot be trusted with limits-adjustments. With clinical patients, where one wishes to avoid saturation and attention artifacts, our experience is that relatively more time must be allowed for situational adaptation, rapport, and auditory learning.

For these reasons we have abandoned the hope of collecting a valid series of limens on a patient by devoting only a few minutes to each limen, attempting to overcome the many unwanted artifactual intrusions by using counterbalancing in the experimental design. We now are resigned to devoting four to five times the amount of

effort usually considered necessary for clinical work of this sort, and we are convinced that to do less is to vitiate one's data past the useful point. If a thing is worth doing. . . . We feel the aposiopesis has real cogency.

As one example of how clinical material can throw light on the reality of the primary loudness factors, we offer the case of Patient JEH, who appeared in our clinic after a vascular accident suffered 12 November 1958 during a 100-lb pressure test. His audiogram on 14 November 1958 was as follows:

250 500 1kc 1.5kc 2kc 3kc 4kc 6kc 8kc

R	0	0	0	5	5	5	10	15	10
L	15	10	5	15	35	60	60	65	70

17 Nov.

L	0	0	0	0	10	40	45	60	60

Bone conduction equalled air conduction. There was complete absence of recruitment, tested R-L at 2kc, and with Békésy audiometry. The speech intelligibility function, though it reached 91% PB correct, was very badly distorted. Speech at 345 words per minute was almost completely unintelligible (L: 8% sentences correctly understood; R: 84%); at 325 words per minute, L: 50%, R: 100%. There was little disturbance of temporal integration down to 0.02 sec duration. There was no diplacusis or deterioration of frequency discrimination. Caloric irrigation of L meatus indicated slight vestibular dysfunction. Neurosurgeon's impression: temporary dysfunction of VIII nerve; organ of Corti probably unaffected.

A complete series of tests of loudness discrimination showed a marked distortion (improvement) of loudness-modulation. Using the saw-tooth modulation of the Allison 21C audiometer, patient yielded the following thresholds at 2 kc in $DL_{75\%}$:

	10 SL	40 SL
R:	4 db	.7
L:	.5	.35

These results, especially at the weaker SL, were so striking that they were repeated several times for the patient's and the experimenter's satisfaction.

However, on a test of loudness-memory, the $DL_{75\%}$ was:

	10 SL	40 SL
R:	2 db	1
L:	2	.8

If the diagnosis is correct, these data indicate that loudness-modulation is primarily subserved by peripheral neural mechanisms but that these mechanisms can be extensively tampered with without in any way affecting loudness-memory.

Experiment VI: ΔI for Loudness/Masking at 1000 CPS

We have seen now that three separate ΔI factors exist, but we had not as yet explored the effects of frequency and overall loudness for the Loudness/Masking area. Accordingly we filled in this information.

The highest-loading test on this factor is a pure tone increment test similar in some stimulus ways to the quantal method. We required six experienced Ss to furnish JND judgments on these increments.

Conditions of Testing

Subject listened monaurally with a PDR-8 phone in a soundproof room. A continuous pure tone, set to the desired SL by adjustments, contained an in-phase increment lasting 0.15 sec. Rise-fall time was 0.01 sec. The interval between increments was 0.85 sec. Subject adjusted a continuously variable resistance by a variant of limits-adjustments as described in Experiment II, until he was ready to report that he could sense the increments about half the time. (This is not necessarily to hear every other increment, since responses have unequal conditional probabilities.) Voltages with and without the increment (made continuous for this purpose) were read and the JND calculated in db. A minimum of five trials was required at every set of conditions. These decibel values were averaged. The octaves 125-4000 and 6000 cps were examined at each of the SLs 5, 10, 20, 30, 40, 60, and 80 db. Complete data on loudness matching was available so that SL could readily be converted to sones or phons.

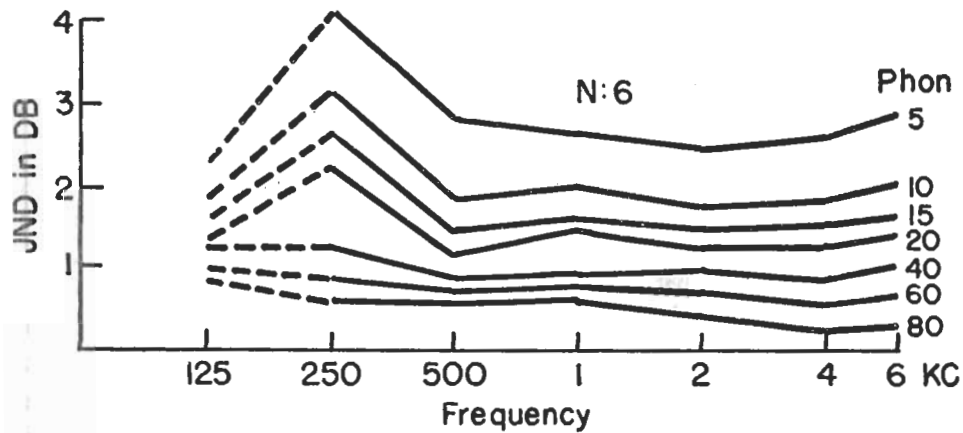## Results and Discussion

Table 10 gives the average raw data,

FIGURE 5. Mean JND in db for Loudness/Masking. Data are interpolated from Table 10 with sensation level converted to phon level.

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TABLE 10. JND in decibels for Loudness/Masking (increments of 0.15-sec duration in a continuous tone), method of limits-adjustments.

125 CPS

S	5	10	15	20	25	30	40	50
RHE	2.3	1.3	1.1	.9	.8	.9	1.3	.9
AGP	3.6	2.7	2.1	1.8	1.5	1.3	1.0	.8
JDH	1.7	1.4	1.2	1.4	1.6	1.5	1.4	1.0
CKM	2.1	1.9	1.8	1.5	1.3	1.1	.9	.7
JJO	2.3	1.6	1.3	1.3	1.4	1.4	1.5	1.3
CRP	3.2	1.7	1.4	1.0	1.0	1.0	.8	.6
Mn	2.5	1.8	1.5	1.3	1.2	1.2	1.1	.9

250 CPS

S	5	10	15	20	30	40	60	80
RHE	4.5	3.4	2.6	2.1	1.5	.8	.7	.5
AGP	5.3	4.1	3.7	2.9	2.0	1.6	.7	.4
JDH	2.7	2.1	1.6	1.4	1.1	1.0	.8	.4
CKM	5.1	3.9	3.2	2.4	1.8	1.3	.8	.7
JJO	4.6	3.7	3.2	2.7	1.9	1.3	.9	.7
CRP	3.8	2.7	2.0	1.6	1.1	.9	.6	.6
Mn	4.0	3.3	2.7	2.2	1.6	1.1	.7	.5

500 CPS

S	5	10	15	20	25	30	40	50
RHE	3.1	2.0	1.6	1.3	1.1	1.0	.9	.6
AGP	2.2	2.2	1.2	1.3	.8	.6	.5	.4
JDH	2.3	1.2	1.1	1.0	.8	.6	.6	.3
CKM	3.4	2.3	1.6	1.2	.7	.6	.7	.5
JJO	2.9	2.4	2.1	2.0	1.4	1.3	1.0	.8
CRP	3.1	2.2	1.9	1.4	1.0	.8	.6	.4
Mn	2.8	2.0	1.6	1.4	1.0	.8	.7	.5

1000 CPS

S	5	10	15	20	30	40	60	80
RHE	3.6	2.4	1.8	1.3	.9	.8	.9	.8
AGP	1.7	1.6	1.3	1.3	1.1	1.0	.7	.6
JDH	2.2	1.8	1.6	1.4	1.1	.8	.5	.3
CKM	2.8	1.7	1.5	1.3	1.0	.8	.8	.7
JJO	3.2	2.2	2.2	2.2	1.8	1.7	1.2	1.0
CRP	2.5	2.5	2.0	1.5	1.2	.8	.6	.4
Mn	2.7	2.0	1.7	1.5	1.2	1.0	.8	.6

2000 CPS

S	5	10	15	20	25	30	40	50
RHE	4.0	2.7	2.3	2.1	1.7	1.4	1.0	.4
AGP	2.4	2.0	1.8	1.4	1.0	1.0	.7	.2
JDH	1.8	1.1	.8	.8	.6	.6	.4	.2
CKM	2.7	1.8	1.3	1.0	.8	.7	.5	.3
JJO	3.0	2.3	2.3	2.3	1.9	1.2	1.1	.4
CRP	.7	.5	.5	.5	.5	.5	.3	.2
Mn	2.4	1.7	1.5	1.3	1.1	.9	.7	.3

4000 CPS

S	5	10	15	20	30	40	60	80
RHE	3.3	2.1	1.4	1.3	1.1	.9	.6	.2
AGP	1.9	1.8	1.4	1.5	1.2	.8	.5	.1
JDH	2.3	1.7	1.4	1.1	.8	.7	.4	.2
CKM	2.8	1.9	1.4	1.2	1.0	.8	.5	.3
JJO	4.4	2.9	1.8	1.1	.6	.3	.2	.2
CRP	1.6	1.1	.9	.9	.9	.9	.5	.2
Mn	2.7	1.9	1.3	1.2	.9	.7	.4	.2

6000 CPS

S	5	10	15	20	25	30	40	50
RHE	2.5	1.7	1.5	1.2	1.2	1.6	.5	.3
AGP	1.0	.9	1.2	1.1	1.1	.6	.3	.3
JDH	2.2	1.3	.9	.7	.7	.6	.3	.2
CKM	3.9	2.9	2.3	2.0	1.4	1.2	.5	.4
JJO	4.3	2.7	2.1	1.8	1.6	1.6	.3	.4
CRP	2.3	1.5	1.2	1.1	1.2	1.0	.4	.2
Mn	2.7	1.8	1.5	1.3	1.2	1.1	.4	.3

and Figure 5 shows the negligible effect of frequency upon the JND in db, the parameter being phon level.

There is little doubt that the bending over at 125 cps of the low-frequency isosonic contours of Figure 5 is due to distortion in the phone and is not truly characteristic of the ear. This region will have to be worked over with a speaker in an anechoic room.

These and previous data can be cast into a form to show the rather surprising fact that *when the judgmental conditions* are comparable, all three ΔI factors are affected very similarly by over-all loudness. One comparison of sets of data at 1000 cps for the three factors is made easy for the reader in Figure 6. A tendency exists for the
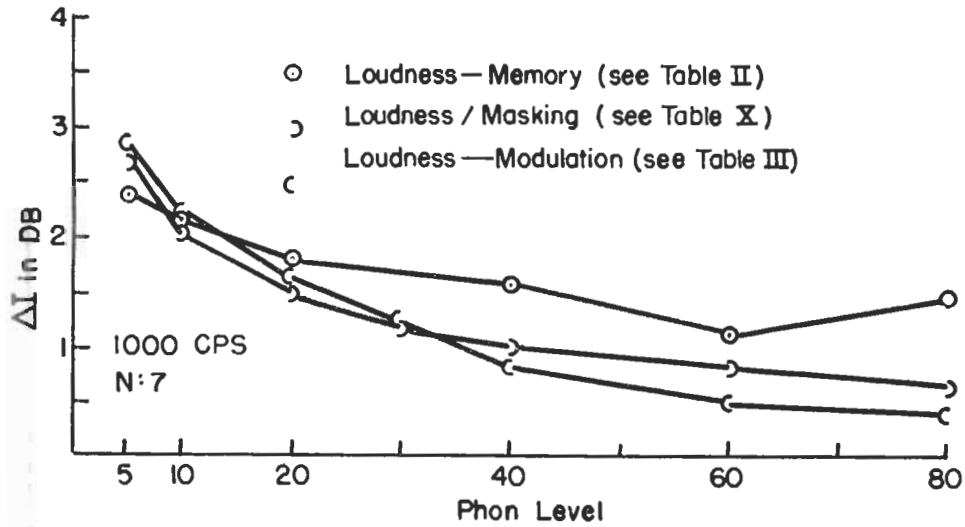
FIGURE 6. Comparison of effect of overall loudness on all three primary loudness factors, under identical judgmental conditions.

Loudness-Memory ΔI to separate from the other two both as to increased sensitivity and as to reduced effect of overall loudness, but the data for Loudness/Masking and Loudness-Modulation are almost identical in the same Ss.

Chocholle (*8*), by giving S control over the initiation of a tone and of an almost instantaneous increment, has maximized the JND for Loudness/Masking. His data will be reported below.

Experiment VII: Parameters of the Loudness/Masking JND

The use of an increment in a steady-state tone has several advantages besides being the purest example of the Loudness/Masking Factor. We were interested in the interactions of the sharpness of onset of this increment and its duration, as well as the overall loudness. Accordingly we carried out such observations in a parametric study.

Introduction

If one examines the JND or the DL_Q reported by previous investigators, the influence can be detected of certain parameters other than sensation level (*38*). For example, Miller and Garner (*61*) in their quantal study used an increment duration of only 75 msec; their data might well have been identical with that on Volkmann's ear (*85, 86*) had they used his 150 msec increments. Chocholle (*8*) on the other hand, whose $DL_{inc\ 50\%}$ mean data are better than any other set reported, used a change of intensity lasting irregularly about a full second.

In addition to the duration of the increment, another parameter arises, namely, the attack front, or rise-fall time, of the increment. For example, Jerger (*44*) used a fairly well-trained group of 10 subjects in an incremental situation, with a duration of 550 msec. This long time should have maximized conditions such that we would predict a JND at 10 db and 40 db SL about 0.5 db better than Jerger found—until we remember that he used a very slow rise-fall time of 0.10 sec against the more usual 0.01 sec transition.

Conditions of Testing

We used 1000 cps for this experiment; conditions of testing were exactly those of Experiment VI, except for rise-fall time, which was varied from 0.005 to 0.05 sec, and duration of increment, which was varied from 0.02 to 2.0 sec.

Results and Discussion

1. *Duration and SL.* Figure 7 shows the effect on the JND of duration of the increment at various SLs; the data are the mean values for seven laboratory Ss.

The data show pretty clearly an asymptote at about 300 msec duration even for very weak tones. This is a little shorter than reported by Garner and Miller (*28*), who found at 40 db the $DL_{inc\ (Q)}$ was still improving at 300-400 msec. Notice in Figure 7 that at 80 db, the JND is within a couple of tenths of a decibel of the maximum even when the duration is as brief as 20 msec.

We will not take time here to develop the consequences of this figure as they relate to the loudness vs. ΔI curve; but it is obvious at a quick glance that the duration of a tone determines its loudness to a degree, which
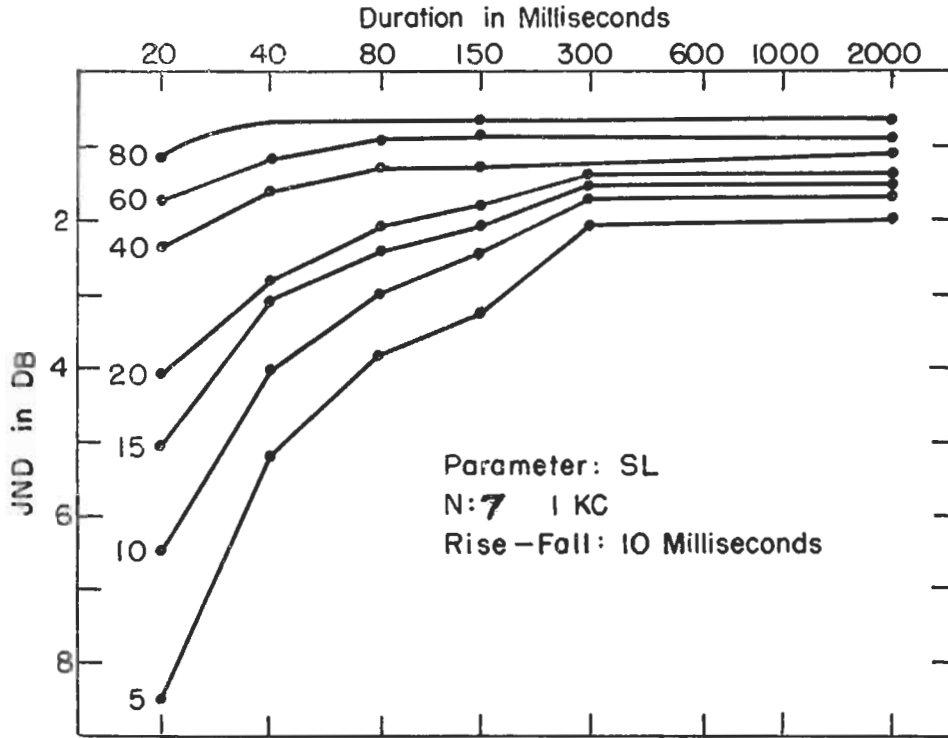
FIGURE 7. Effect of duration of increment upon JND for Loudness/Masking; method of limits-adjustments.

in turn may determine sensitivity. This is not the whole story, however, as we can determine from Garner's paper
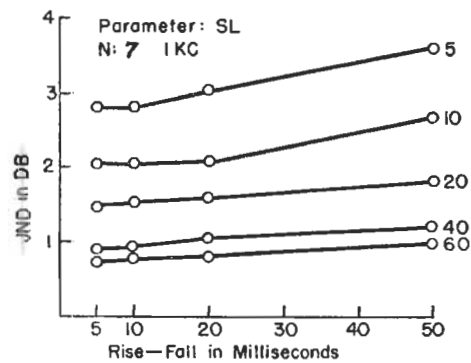

FIGURE 8. Effect of rise-fall time of increment upon JND for Loudness/Masking; method of limits-adjustments.

(27) on the loudness of short tones. At 40 db intensity (about 23 db SL), for example, increasing a 1000 cps tone from 20 msec to 100 msec will increase its SL by only 2-3 db at most, whereas we see from our Figure 7 that an increase of about 30 db would be needed to explain the improvement in the JND as the 23 db SL curve moves from 20 msec to 100 msec duration.

2. Transition Time and SL. Figure 8 shows the effect of rise-fall time on the JND at various SLs.

Previous investigators have varied from Chocholle's and also Garner's rather abrupt onset, and Békésy's 3-msec onset, to Jerger's 100 msec and to Churcher, King, and Davies' 3 sec.
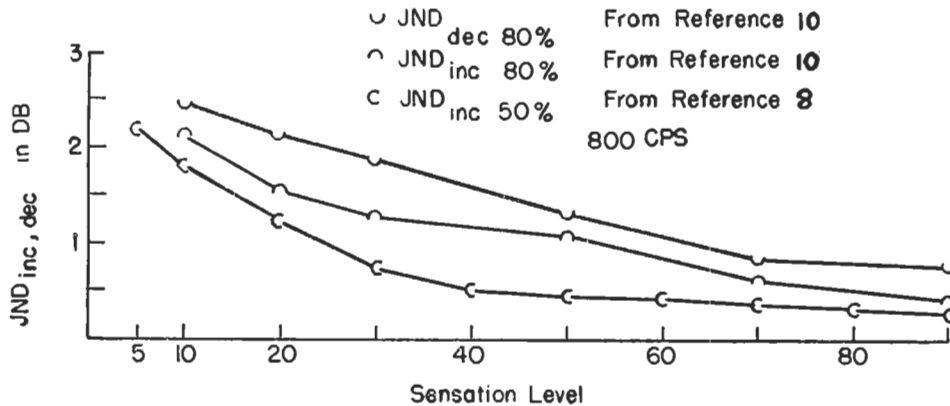
FIGURE 9. Effect of overall loudness upon JND$_{inc}$ and JND$_{dec}$.

We find in Figure 8 that attack times from a very few msec to about 20 msec are quite equivalent but that beyond 20 msec a discernible deterioration takes place up to the limit we used of 50 msec.

For the present, the usefulness of these data lies in delimiting the effect of these parameters on the ΔI with a view to reconciling certain seeming experimental discrepancies from one laboratory to another. Their usefulness in commenting upon the growth of loudness and the process of temporal integration must form another chapter.

Churcher, King, and Davies (*10*) accomplished a smooth transition from one intensity level to another in from 0.25 to 3 sec; S was required to signal when an increment (or a decrement) occurred. The intensity was changed back to its steady state over a period of 10 sec so that in an 'increment' series, for example, S was sensible only of loudness increases. In this situation a negative time-error appeared such that decrements were about half again more difficult than equal-intensity increments, and we plot the mean

JND$_{80\%}$ for both for the four Ss in our Figure 9. The reader will note the profound effect of overall loudness on these data, as all later data from Loudness/Masking have verified.

Chocholle (*8*) maximized the method of constant stimulus differences in Loudness/Masking by giving experienced Ss control over the initiation of increments and demanding 100 judgments for each value of quick but click-free increments. Full data on two Ss, including the psychophysical functions, are provided at 200 cps up to 50 db SL, 1000 cps up to 100 db SL, and 10,000 cps up to 60 db SL. Mean curves of DL$_{inc\ 50\%}$ versus overall loudness are given on three Ss at 200 and 10,000 cps, and on four Ss at 1000 cps. These data are very interesting from several points of view. The shape of the individual psychometric function will be discussed later on. Here we wish to point out the general similarity of Chocholle's Figure 9, relating DL$_{inc\ 50\%}$ to SL at 1000 cps, to other equivalent curves using a Loudness/Masking stimulus. Our Figure 9 compresses the individual data of Chocholle's Figure

9 and shows the same sort of trend with SL as Churcher, King, and Davies with the same sort of stimulus, even to the absolute size of the ΔI. Indeed, when we consider only the JND_{Inc} of Churcher, King, and Davies and allow a fraction of a decibel for these workers using an 80% rather than a 50% criterion, the data become statistically identical.

A few remarks are appropriate here on another sort of stimulus condition involved in the Loudness/Masking Factor, namely, a noise-in-noise ΔI.

Experiment VIII: The Loudness/Masking
ΔI for Complex Sounds

Introduction

Montgomery (62) first presented data on sensitivity for complex sounds. He used white noise and a plan which allowed S to initiate the stimulus sequence, allowed no interval of silence to intervene between two bursts of noise to be compared, and for any judgment allowed S to listen to a pair of bursts repeatedly until he made up his mind. (The worst plan was to combine the reverse of these three conditions.) He reported ΔIs of 0.2 - 0.8 db.

Karlin (47) presented data for 50 men given the Harvard Test No. 7, discrimination for bands of noise. The $DL_{75\%}$ was approximately 0.5 db. Harris (31) reported on extensive use of this test, confirming Karlin in detail.

Miller (60) first treated in detail the $DL_{Inc(Q)}$ as a function of sensation level. Two Ss using a quantal procedure made judgments on the presence of increments in either a 'square-wave' or 'random' noise. The data show a slight improvement in sensitivity from 20 through 100 db sensation level (an improvement from about one-half db to about one-third db), but a sharp deterioration in sensitivity to 3.2 db as the SL drops from 20 to 3 db.

Postman (76) reports a minimum $DL_{75\%}$ of about 0.6 db for interstimulus intervals of 0-6 sec and SLs of 35-75 db.

Conditions of Testing and Results

Our work in the ΔI for noise has been reported in two previous communications (33, 34) and will be summarized only briefly here. We varied SL, psychophysical method, and interstimulus interval. For paired noise-bursts at 55 db sensation level with forced 'louder'–'softer' judgments, the $DL_{75\%}$ ranged at random through 0.5-0.72 db at six inter-stimulus intervals 0-1 sec.

At the same SL and at 0 interstimulus interval, Postman's Ss by a comparable technique yielded 0.67 $DL_{75\%}$; at the 1-sec interval his Ss yielded 0.74 db. These are highly comparable results.

In another substudy with this same method, the almost negligible effect of overall loudness was shown, but a profound effect of psychophysical method. In Figure 10 are shown the curves of $DL_{75\%}$ at SLs 5, 10, 15, and 40 db for three Ss, not at all our three most acute listeners. (For 10 motivated but untrained Ss the mean DL_{75} for the same conditions was 0.70 db at all sensation levels.)
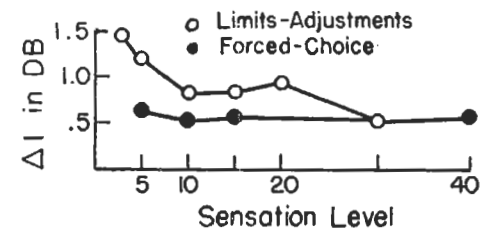

FIGURE 10. Effect of judgmental condition upon $DL_{75\%}$ for noise.

When, however, we allowed these same three Ss to report only when they heard every second an alternation in noise level, we obtained JNDs by the

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method of limits-adjustments which did vary regularly with sensation level, as Figure 10 also shows. At the same time, the absolute sizes of the ΔIs at the 5 db SL are about 2:1 in favor of the forced-choice method.

In still another substudy we duplicated the experiment of Miller (*60*) using $DL_{inc(Q)}$ but instituted polygraph scoring so that the false-positive responses could be eliminated. This brings the $DL_{inc(Q)}$ down to believable magnitudes at the weaker sensation levels (see Figure 3 of Reference *34*), and renders the $DL_{inc(Q)}$ comparable in every way to the JNDs of the previous paragraph.

Pollack (*73*) has also square-wave modulated a white noise and calculated the mean JND for five Ss at SLs 5-80; his data are practically identical with those of Harris using a nearly equivalent method of limits. The three experiments are compared in Figure 11.
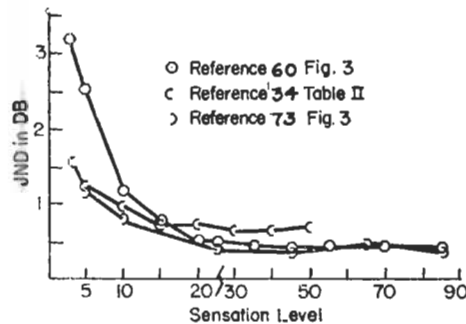

FIGURE 11. Effect of overall loudness upon JND for noise.

Discussion

Part of our interest in the ΔI for noise comes from noise being at one end of the pure tone vs. noise continuum, and part of our interest comes from noise, especially bands of noise, being much closer than pure tones to the speech situation. Flanagan (*21*) has

found the $DL_{inc\ (50\%)}$ for stylized vowel sounds to be about 1.5 db at about 50 db SL; the stimulus was a complex sound with peaks at the frequencies 120, 500, 1500, 2500, and 3550 cps. Flanagan's Ss used a 'same' or 'louder' judgment; it is clear that the $DL_{50\%}$ is somewhat larger than the $DL_{75\%}$, since the latter encourages guessing and maximizes the use of subliminal cues. In the present paper the method most nearly like Flanagan's is the method of limits-adjustments. Now note from our Figure 2 that our seven Ss at 50 db SL gave an average JND of 1.5 db for pure tones, while from our Figure 10 we see that four Ss gave a JND of only about 0.5 db *for noise* by the identical method. In other words, Flanagan's $DL_{inc(50\%)}$ for vowels, 1.5 db, is almost exactly the same as ours for pure tones but differs from our $DL_{inc(75\%)}$ for noise by a factor of 3. Evidently the ΔI for speech vowels partakes more of the nature of tones than noise.

* * * * *

Further Remarks

The reader will have noted that in all the work so far on the ΔI for complex sounds, no mention has been made of the ΔI for pure tones masked by noise. This omission is because it was for a long time not clear to us whether a Pure Tone Loudness-Memory ΔI test comes to have representation in the Loudness/Masking factor if a noise background is added. Our data cannot yet be regarded as proof, but an informed guess is that the primary nature of a Loudness-Memory or -Modulation test is *not* changed. Our data show, at least, that adding a noise does not change the effect of overall loudness on a Loudness-Memory Test.

Experiment IX: The Loudness-Memory ΔI for Masked Pure Tones

In considering the remarkable resistance to reduced SL of the ΔI by Loudness-Memory (forced choice), in which loudness in and of itself fails to affect the $DL_{75\%}$ appreciably (albeit a tone 5 db above threshold sounds really very weak), one inquires what sort of condition *might* cause the ΔI to deteriorate in some regular manner? We decided to introduce noise as a background against which discrimination for a tone would be measured as the level of the tone varied above the level of the noise (67).

Previous Studies

In an attempt to assess the DL for the Morse Code radio range signals A and N under simulated flying conditions, Flynn and Newman (22) employed S/N ratio as the independent variable. This ratio was varied from −10 to 50 db (re 1 mv) with the signal fixed at six different levels between 86 and 124 db SPL. The course of change of the DL with S/N ratio for all levels of the signal showed a steep initial drop from about 5.5 db at S/N of −10 db to 0.3 to 0.5 db, depending on the level of the signal, at S/N of about plus 10 db and remained nearly constant at one or another value in this range. The A and N signals were interlocked so as to produce, phenomenologically, the N signal (perforce an interrupted stimulus) against a steady tone of the same frequency and this complex in turn occurred against a background of static-like noise. The method of adjustments was used with unlimited time afforded S for his judgment.

The work of Tonndorf *et al.* (90) will be discussed later on. Another experiment of this sort is that of Woodhouse (92), who, in the course of investigating sensitivity versus the frequency of repetition of pairs of stimuli, did a subsidiary study in which she varied the level of the noise about that of a tone which was fixed in the first case at 53 db SPL and in the second at 63 db SPL. The $DL_{75\%}$ was nearly unaltered at 1 db in both cases. (However, the variability of the limen rose markedly as the S/N ratio decreased.)

Conditions of Testing

Our apparatus and procedure were in essentials identical to those of Experiment I, except that a white noise 40 db above its own threshold was mixed with the signal and controlled with additional attenuators.

Results and Discussion

Figure 12 contains the mean $DL_{75\%}$. It is clear that there is no consistent effect of S/N at either frequency. This is, of course, quite divergent from the data of Flynn and Newman (22) and of Tonndorf *et al.* (90), though it agrees in general with the work of Woodhouse (92). But note that Woodhouse was the only other worker to use a Loudness-Memory test, while
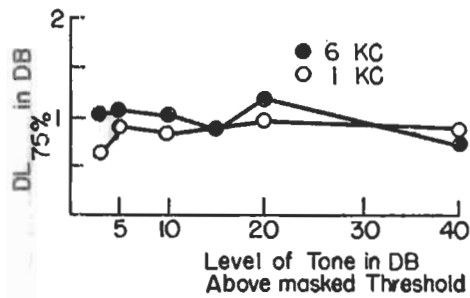
FIGURE 12. Effect of noise-masking upon Loudness-Memory, with situation optimized. Data from reference 67.

Flynn and Newman used a Loudness/Masking and Tonndorf a Loudness-Modulation test.

It might be asked whether the ΔI remains relatively uninfluenced if the level of the *noise* is established at several different points and the signal is allowed to vary above this as in the present experiment. While this parameter has not been examined in the experiment under discussion, there are data which bear on this question. Tonndorf *et al.* (*90*) used noise in an attempt to simulate 'recruitment' in normal hearing Ss. They obtained ΔIs for an amplitude-modulated tone of 800 cps 5 to 40 db above a wide-band noise. ΔIs in the range 3.5 to 1.5 db persisted in their Ss from the no-noise condition through a noise of 70 db (SPL). Indeed, the graphs displaying difference limen as a function of level of tone were nearly duplicates.

Experiment X: Group Data

For the benefit of those readers, either clinical or psychological, who are interested in individual differences, the following data are offered:

1. The $DL_{75\%}$ for Loudness-Memory

In order to discover what the untrained ear could do with the forced-choice $DL_{75\%}$, we taped tests of the $DL_{75\%}$ in a pattern similar to that of Experiment I except that 0.5 db variable steps were used rather than 0.2, the range extended from plus 4 to minus 4 db around the standard, and the level of difficulty proceeded regularly from easy to difficult.

Frequencies tested were 125, 1000, and 6000 cps, at the 1-sone loudness level (these loudnesses at 125 and 6000 cps were derived from the ASA loudness vs. loudness level curves). In case an S's data were unduly erratic in group testing, he was called in for more careful individual testing. No S who started the test was dismissed until a satisfactory $DL_{75\%}$ had been obtained.

Table 11 gives the distributions of $DL_{75\%}$ in db. These means are about a half-db larger than for the experienced Ss of Figure 1 at equivalent loudness, but they show that untrained Ss are nevertheless capable of quite fine discrimination with the forced-choice method.

2. The $DL_{75\%}$ for Pure Tone Loudness/Masking

Our data here come from the taped test (M) of Experiment V, the DL_{75} for an increment of 0.15 sec in a 1000-cps tone of 1.5 sec duration, with a '1'-'2' forced judgment. This distribution is in Table 12.

3. The $DL_{75\%}$ for Loudness-Modulation

Our data here also come from Experiment V, test (E), the $DL_{75\%}$ for sine-wave modulation in one of a pair of 2.5-sec tones, with a '1'-'2' forced judgment. This distribution is also in Table 12.

The great contribution to our knowledge of amplitude-modulation made by Zwicker, Feldtkeller, and their colleagues (19, 94, 95, 96) is now well

TABLE 11. Distributions of $DL_{75\%}$, Loudness-Memory, at three frequencies, for untrained subjects.

$DL_{75\%}$ Intervals	125 CPS	1000 CPS	$DL_{75\%}$ Intervals	6000 CPS
.2- .39		1	.6- .99	3
.4- .59			1.0-1.39	9
.6- .79	3	4	1.4-1.79	6
.8- .99	7	6	1.8-2.19	1
1.0-1.19	2	2	2.2-2.59	1
1.2-1.39	1	4	2.6-2.99	1
1.4-1.59		2	3.0-3.39	
1.6-1.79		1	3.4-3.79	1
1.8-1.99				
2.0-2.19	1	1		
2.2-2.39	1			

TABLE 12. Distributions of $DL_{75\%}$ for Loudness-Modulation and for Loudness/Masking at 1000 cps for untrained subjects.

$DL_{75\%}$ Intervals in Decibels	Loudness-Modulation (Test E, Exper. V)	$DL_{75\%}$ Intervals in Decibels	Loudness/Masking (Test M, Exper. V)
1.0-1.99	8	0- .49	1
2.0-2.99	28	.5- .99	8
3.0-3.99	33	1.0-1.49	52
4.0-4.99	22	1.5-1.99	23
5.0-5.99	7	2.0-2.49	11
6.0-6.99	5	2.5-2.99	6
7.0-7.99	5	3.0-3.49	5
8.0-8.99	4	3.5-3.99	4
		4.0-4.49	2

known through the publication of their book (20) on the general subject of modulation. Zwicker (94) first provided normal JNDs in % modulation for sine-wave amplitude modulation at 1000 cps over a wide variety of modulation rates and loudnesses. Zwicker and Kaiser (96) then worked over a major portion of the auditory area using a 4-cycle modulation rate. Their results, easily converted to JND in db, furnish excellent norms of this auditory trait.

The large numbers of men tested by Tonndorf *et al.* (90) also on amplitude-modulation, form likewise an important source of normative data.

Discussion

Our data from these group studies, all at about 40 db SL, show a wide range of individual ability in all three factor areas, even that of Loudness/Masking. It is commonly thought that although the audiogram may vary quite widely in a group, masked indices either absolute or differential remain pretty much the same from ear to ear. Here we see differences of the order of 10:1 with Ss who have had several days of practice, with knowledge of their individual results upon request, and who are somewhere near an asymptote of their first learning plateau.

General Discussion

The Relation between the ΔI and Broader Theories of Excitation

It is clear that the real *raison d'etre* of our concern with the intensive limen is its bearing on larger questions. To know that the average ΔI is such and such a quantity is interesting, but only as a species of curiosa. We seek such data for their wider relevance.

The basic importance of the ΔI is bound up with general theories of excitation, which have to explain not only absolute but also differential sensitivity, and form a long chapter in psychophysiology. A few general remarks will not be out of place here. We recall first that differential sensitivity (ΔI/I) is to a first approximation constant for each of a wide range of species, tissues, and stimulus intensities. It is a universal rule that the organism responds not to absolute but to relative increases. But the extreme generality implies to most students of the problem that the explanation for this first-order constancy is physiological, or at least peripheral to the nervous system. The sense organ is often thought of as a buffer for the nervous system, and a compressor of external energy in approximately logarithmic fashion.

Békésy (*1*) constructed an equation which approximately predicted the ΔI data of Knudsen (*48*), using a variation of a general excitation theory which states that the electromotive force which stimulates the nerve fibers will vary with changes in salt concentrations in the germane tissues. For audition, according to this theory, the sensation arising from an acoustic pressure must be proportional to a change in concentration and hence to an electromotive force which stimulates the nerve fibers. This electromotive force is related to the logarithm of the concentration c, and the excitation E in response to an increase aJ in acoustic pressure is thus

$$E = b \log \left(1 + \frac{a}{c} J \right),$$

and a differential sensation, ΔE, is a changing constant corresponding always to the smallest pressure change discernible:

$$\Delta E = b \log \frac{1 + \frac{a}{c} J + \Delta J}{1 + \frac{a}{c} J}.$$

But this can be written:

$$\frac{\Delta J}{J} = X + \frac{Y}{J}; \text{ where } X = \frac{a}{c} Y.$$

Now for the weakest pressure, $Y = J_v$ (at the absolute threshold of activity) and at pressures where the ΔI/I becomes constant $X = \Delta I/I$. Following this chain of reasoning, then

$$\frac{\Delta J}{J} = \frac{\Delta I}{I} + \frac{J_o}{J}.$$

Békésy replots Knudsen's data according to the equation he derived and shows good agreement at the frequencies 200 and 1000 cps.

In this endeavor Békésy assumed the validity of Fechner's law on the relation between sensation and log stimulus. More recent psychological literature has not been entirely sympathetic to this sort of formulation.

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An early generation of psychologists suggested that as the intensity of sensation increased, an increasing inhibition was exerted on the sensation of difference, and that thus the absolute amount of intensity increment needed for one DL was greater with more intense stimuli. But the evidence from isolated tissues and lower animals, where such could hardly occur, is clear, and we do not today seek for the constancy of Weber's fraction in terms of inhibition.

A second generality is that a closer look at the Weber fraction uncovers a universal rule that differential sensitivity is worst near absolute threshold and improves up to comfortable levels. What one must do here is to reverse our field and explain why under certain conditions Weber's fraction is *not* constant.

It may seem at first to be going far afield to seek explanations of differential auditory sensitivity in terms of general theories of nerve-muscle excitation. But recall the striking similarities and analogies in the sense organs to the phenomena, in less organized tissues, of chronaxie, the effects introduced by repetitive stimuli, temporal patterning of the stimulus, and log conversion of stimulus intensities.

At least one general theory can partially describe the data of differential auditory sensitivity. For example, one very general formulation, attributed by Piéron (70) historically to Pütter, thinks of excitation as the disturbance of an equilibrium; the model is of three substances, an initial substance A yielding (reversably) substance S sensitive to environmental stimuli; and an excitatory substance E. Now if stimulus intensity can be assumed equivalent to the velocity of the action S → E, and if differential sensitivity can be assumed related to a constant *additional* amount of E, an equation can be written showing that there exists a U-shaped relation between stimulus intensity and differential sensitivity. The cogency of this model lies solely in the fact that many sets of intensity discrimination data, particularly in vision and of course the data of Riesz, show just exactly this U-shaped curve. Hecht has been most persuasive in using one form of this model to explain differential intensive sensitivity of the eye in terms of a constant additional amount of a substance. But in the eye photochemical substances are well known to exist and in fact show behavior not inconsistent with the model. For the ear the model has less immediacy primarily because we cannot so readily envisage substances (or even electrical potentials). As a formal exercise, the model may be said to fit certain auditory data. On the other hand, most of the data in this paper on the relation between differential sensitivity and overall loudness definitely do *not* exhibit a U-shaped curve. Other models of excitation—mechanical, electrical, mathematical—fail to predict differential intensive sensitivity with any reality. The writer concludes that not much if anything is gained for our particular purpose by seeking more and more remote analogies.

A Closer Look at the Full Psychometric Function

In the first place we can distinguish two relevant features of sensitivity data, the threshold itself and the form and/or slope of the psychometric function. Let us consider the shape of the whole

curve first before we take up the particular point on that curve denominated as 'threshold.'

1. The Shape of the Psychometric Function. In the initial studies in psychophysics a century and more ago it was noted that the form of the curve was sigmoid. The relation to an ogive was obvious, and the concept of probability was immediately applied, first to the distribution of sensori-neural factors favoring discrimination and also to the distribution of sensations to a repeated stimulus. These ideas were polished by the turn of the century and have not been essentially changed or added to since then, except that many thinkers now consider both distributions to amount to the same thing. Thus, today we consider that the sigmoid shape of the psychometric function arises from there being a normal distribution of sensori-neural events as a consequence of every stimulus; there are postulated enough of these events, some favorable and some unfavorable to a positive response, so that for a series of closely-spaced stimulus increments one has a smooth ogival transition from the 0% favorable to the 100% favorable distribution.

Boring (2) is usually credited with suggesting that there may be some sort of step-wise rather than smooth transition of sensory experience as the stimulus increment is raised in small amounts. Piéron (69) also has insisted on the possibility. If so, one would have evidence for the *first* assumption in auditory 'quantum' theory, that the sensorium works as if built up of sensory- and/or -neural units operating in 'quantal' or 'all-or-none' fashion. Because of the more usual meaning of quantum, the writer prefers Piéron's

term neuroquantum, thus designating the physiological aspect of the idea; and we use the term 'saltatory sensation growth' to refer to S's experience. Békésy actually found something approaching this step-wise rise in sensation for intensive discrimination. He used well-trained subjects to study sensitivity by the constants method, with no appreciable interval of time between the two stimuli to be compared in loudness.

Of course, there was no critical stimulus increment below which it was never sensed, and above which it was *always* sensed. A *second* assumption is therefore brought into play, that a single sensori-neural unit fluctuates in sensitivity; a continuous background stimulus may not be sufficient to excite the unit. If not, that particular stimulus energy would be said to be wasted, except that the *third* assumption is invoked, that temporal and spatial neural summation occurs such that the 'wasted' energy is said to be utilizable in case a stimulus increment *smaller* than critical is applied. Here the sub-critical increment has a subliminal effect which can summate with the residual or 'wasted' effect of the background stimulus, to excite an additional unit and thereby produce an accretion of sensation and thus a positive response. But note that the subcortical increment can be smaller when the residual wastage is larger.

By these three assumptions one avoids the necessity of predicting a truly step-like rise in sensation and thus in the psychometric function, and predicts instead a straight line for the function. The straight line arises as the integration of equal probabilities, one amount

of residual wastage being (so far as we know) as likely as any other.

Stevens and Volkmann (*86*) point out not only that a straight-line function should result if the quite rigorous demands for stimulus and timing controls are met, but further that the stimulus increment heard just more than 0% of the time should be the stimulus correlate of one neural unit, and that least increment heard 100% of the time should be the stimulus correlate of two neural units. Thus both the linearity *and the slope* of the function is predicted by 'quantum' theory. The classic probability hypothesis does not predict the slope.

Two experiments should be cited to show that the step-like character of the response is at least exceedingly difficult to recover. Brown (*5*) found a smooth rather than a step-wise segment of the psychometric curve when he put steps of less than one DL under a microscope. An array of variable stimuli of sub-DL dimension yielded smooth data around 50%. Also, Chocholle (*7*) found that a smooth gradation of latencies appeared in response to stimuli which differ by *less* than 1 JND.

The discrepancies are well known between those who find full or partial support for a theory of saltatory growth of sensation and those who find no support. The writer feels that the all-or-none principle introduces the logical possibility of a saltatory increase in sensation, if the overall loudness is so weak that only relatively few sensori-neural units are in play; but the multiple innervation and convergence of the external hair cell-neurone connections are such that it seems physiologically fantastic to speak of a single 'quantum' or

even of a few 'quanta' at any even moderate loudness. The saltatory character of sensation growth has never directly been reported for ΔI_Q by a listener, but arises, when it does, as an inference on the graphing table. As such, a step-wise growth of loudness may be disregarded at least in interpreting auditory experience.

We do not yet have the data needed to bear on one important question here, how the 'quantal' stimulus increment ΔI varies with SL. (See Neisser (*63*) for a recent full summary.) The data on Volkmann's left ear (*85*) at five SLs were complicated by using either a smooth or an abrupt onset of increment; Corso's (*11*) five individual functions at four SLs contained only two linear functions out of the 20. Even Neisser's data do not inform us. What we really wish to know here ultimately is whether the ΔI arises from a constant number of additional nerve impulses per unit time, a constant percentage of additional neural firings, or is associated with some other neural complex.

2. The Relative Size of the ΔI. We now pass from the shape of the psychometric function to the matter of the magnitude of the limen itself. Psychologists are fond of pointing out that the human sensorium in general has no true zero but responds to relations and changes. A simplifying concept (though probably erroneous) would be that, once the sensorium has reached a stage of adaptation to any constant stimulus, an additional stimulus increment effective to cause a change in sensation would always involve a constant. This constant would be some sensori-neural complex. In vision, for example, many

physiologists follow Hecht and Wald in the argument that (at least for most levels of illumination) an effective stimulus *increment*, ΔI, always involves the decomposition of the same amount of photochemical substance and the same number of additional nerve impulses. (It should be said that some dissatisfaction has apparently risen over Hecht's formulations of two decades ago. If it turns out that the JND is not simply related to photochemical breakdown as has been thought, it may be that in the visual area as well one is driven to seek a solution in the central nervous system. It may be of interest here to note that a single JND in visual brightness is not mediated by a constant number of quanta of visual energy. It would seem then that in vision a single JND is related to some retino-neural mechanism now the subject of much discussion among our optic friends.)

In audition, one would first wish to know even roughly the number of nerve impulses at a given instant for a variety of loudnesses; the fairly adequate data now at hand as summarized in this paper could then be used to calculate the constancy of the ΔI in neurological terms over the intensity range.

Stevens and Davis (*84*) give a first approximation to a physiological correlate of loudness, over a wide intensity range. They first had human subjects adjust two tones, of different frequencies, to equal loudness, then led these tones to the ear of a guinea pig. The electrical output of the animal ear showed that equal loudness yields equal potential. They showed that the auditory nerve potential followed the cochlear microphonic faithfully for the

most part, and they argued fairly conclusively that loudness depends upon total number of nerve fibers being activated at any instant (not, be it noted, on number of impulses per unit time). The writer finds equally persuasive the argument of Hood (*40*) from purely psychoacoustic data to the effect that total number of active fibers is the loudness determinant.

Stevens and Davis further showed that the curve of integrated JNDs from Riesz does not adopt at all the same shape as the loudness function. Therefore, they reasoned, a JND at one region of intensity is not necessarily equal in subjective magnitude to a JND from another intensity region.
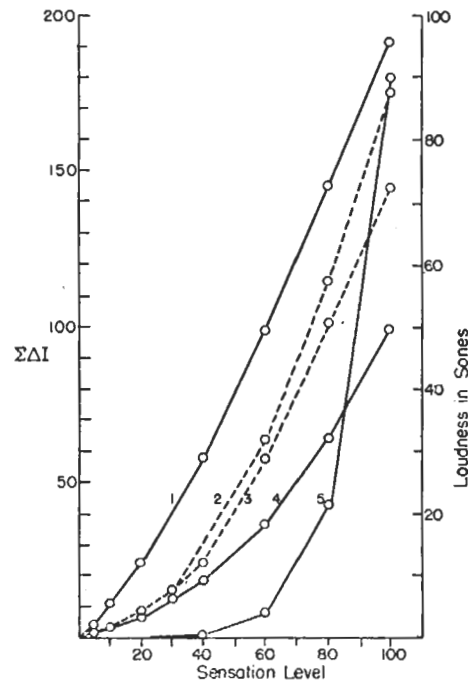

FIGURE 13. A comparison of the shape of the A.S.A. loudness function with several curves of summated ΔI. Curve 1: Experiment I; Curve 2: From Riesz (*81*); Curve 3: Experiment II; Curve 4: Experiment VII; Curve 5: The loudness function (ordinate on right).

Now if we take the data not from Riesz but from any of several of our own sets of results, we find in some cases an even greater disparity between the loudness function and the curve of integrated ΔIs (see Figure 13). By no linear manipulation of ordinates could the two sorts of data be said to coincide. We may conclude therefore that no set of intensity discrimination data will cast up the simple rule that ΔIs are subjectively equal.

We have definitely advanced our ideas, however, by this conclusion. If ΔIs at different intensity regions do not contain the same number of millisones, then the ΔI is not related to the number of additional active nerve fibers *in the same way* that loudness is related; but it obviously is related in *some* way to number of additional active nerve fibers. It may be, for example, that the ΔI is related to a constant percentage or, more likely, to some sliding ratio of number of additional fibers activated. Our best guess, following Stevens and Davis (*84*), is provided by a look at the way the ΔI is related to loudness. We plot the size of the $DL_{75\%}$ in millisones against the overall loudness, in Figure 14, and see that as the overall loudness increases, the $DL_{75\%}$ contains more and more millisones. If we may refer once again to the assumption that loudness is related to number of active fibers, Figure 14 shows us that $DL_{S75\%}$ from extremes of intensity (10 db to 100 db SL) 'use up' neural units varying over a 3-log range! Evidently by no stretch of imagination or margin of experimental error could a ΔI depend upon a constant number of *additional* units, or even a constant additional fraction of units. As overall loudness

increases, the organism needs at first a sizeable fraction of additional loudness, in some cases over two-thirds, before an additional JND is discerned but becomes more and more efficient until at 100 db SL an additional 1% of loudness is sufficient to yield a JND.

No other aspect of the neurophysiology of audition acts just in this way, to the writer's knowledge, and no very good analogy comes from vision. Computations of the fractional energy needed to arouse one JND of brightness can be made from recent data of Thomson (*88*) on the central fovea. Numerous and unexplained irregularities exist among closely adjacent hues, but if we take the fairly typical wavelength of 560 mu, we see that at near-threshold level the fraction of energy (erg/sec) for one JND is about 70%, while it reaches a minimum of about 21% at one log unit higher intensity. About the lowest fractional addition for any wavelength (510 mu at an intensity of 16.5 erg/sec) is 15%. At higher intensities the fraction is usually larger than a minimum found at two or more log units weaker than the maximum intensities studied.

Evidently the ear is able to operate more and more efficiently up to intensities which begin to be annoying or even deleterious, whereas the eye is not so well able to break down the higher intensities into discriminable steps. From Thomson's data it can be calculated that the JND near threshold is about 2.3 db for the 560 mu light, roughly comparable to the case for the 1000 cps tone; but the minimum JND is about 0.85 db for the light, whereas the minimum JND for the tone is commonly half that value. This is, of course, the same order of magnitude, and we
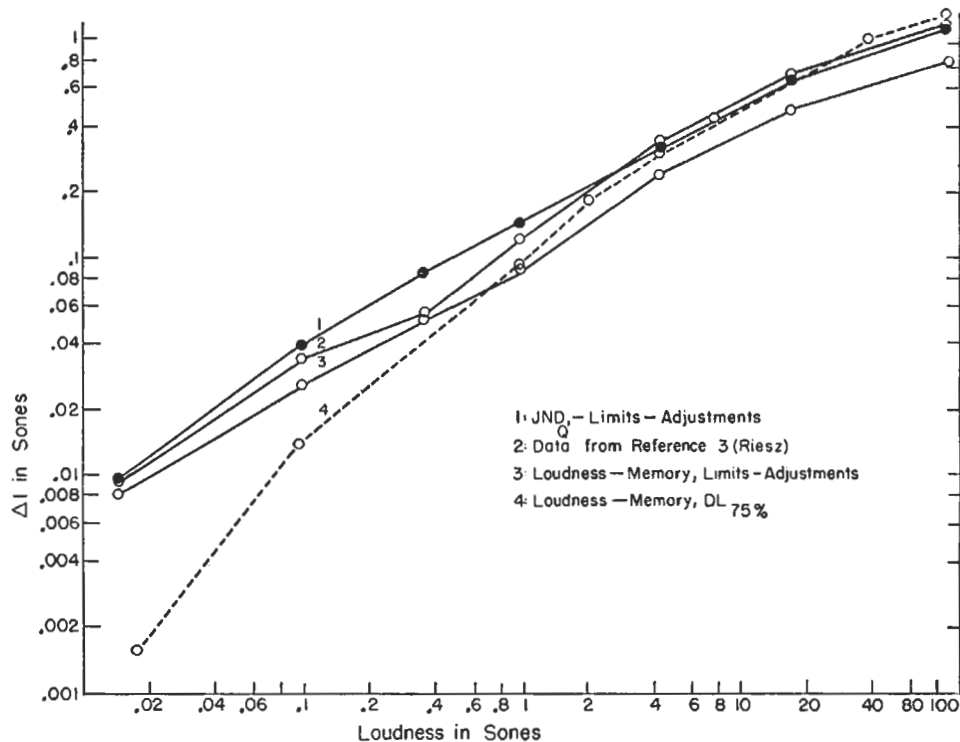
FIGURE 14. The relation between overall loudness and the size of the ΔI in sones.

make really more of the similarity than of the difference; except that we emphasize the ear's ability to continue to profit from an increased energy input, as contrasted with the early maximum efficiency gone through with the eye.

Perhaps a more convenient way to remember the relationship is given in Figures 14 and 15, where over the whole intensity range we plot sone values and fractional loudnesses respectively of single JNDs. Clearly a smaller and smaller fraction of total loudness is needed to yield a JND.

What Is the Relation Between ΔI and ΔF?

Several workers have (mistakenly) supposed that the ear works like a

physical system such that an improved ΔI must be 'paid for' with a deteriorated ΔF. However, Fournier (23), using the modulation experiment to explore both pitch and loudness on defective as well as on normal ears, found that for the most part there was no relation *except for one* type of deafness, namely, auditory trauma with the 4000 cps dip, where pitch discrimination was *always* deteriorated along with an improvement of loudness discrimination.

Schubert (83) has published a case of pitch deterioration in a perceptive deafness of traumatic origin. Both pitch and loudness are distorted.

Zwicker and Kaiser (96) using practically the same frequency-modulation technique as Schubert, report one case of perceptive deafness in which pitch
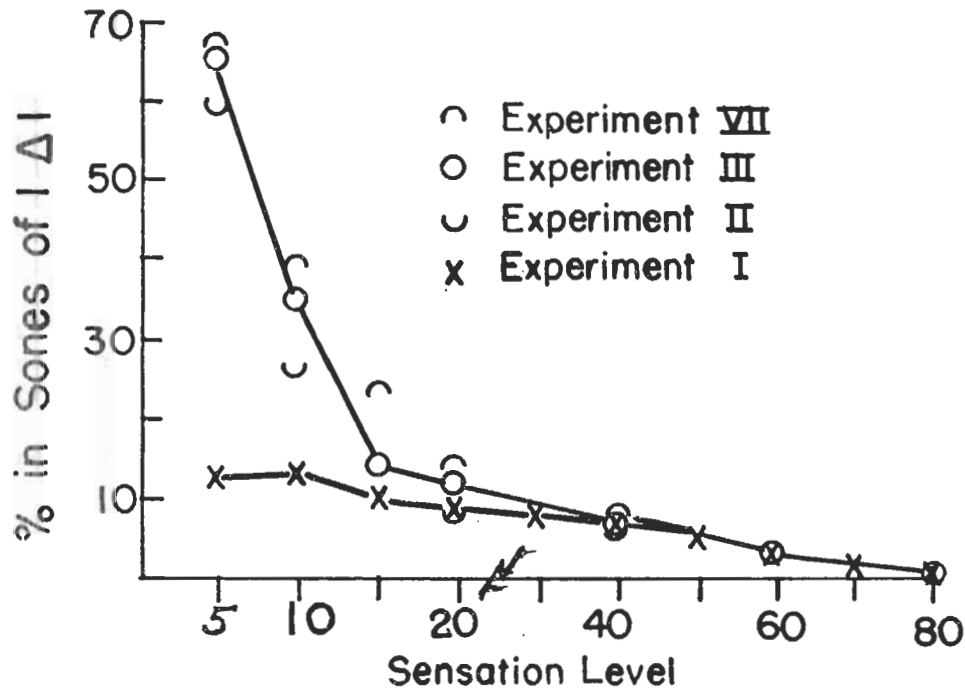
FIGURE 15. The relation between sensation level and the percentage of the overall loudness in sones which constitutes one ΔI.

deterioration was found through that portion of the auditory area affected by the disorder. Zwicker (95) later showed that this same patient had a pitch-deterioration pattern very similar to that of a normal-hearing observer masked by a band of noise in the high-tone region; we assume that the patient had recruitment.

Our data (37), however, make it clear that recruitment of any type, even quick and complete with over-recruitment, can occur without any pitch deterioration whatever. Of the 15 patients who did not show pitch deterioration, six showed quick and complete recruitment; the others showed delayed recruitment (four cases) or had cases of purely conductive or heavily conductive mixed deafnesses and showed no recruitment in our tests (five cases).

All of our data thus point to the conclusion that there is no theoretical necessity for every case of recruitment to be accompanied *pari passu* by pitch blurring.

There were five clinical cases in our series which showed simultaneously an improvement in the ΔI and a deterioration in the ΔF. When, however, we come to examine the otological descriptions, no especial pattern appears. The shape of the recruitment curve, often an important clinical sign, is always of the Quick, Complete, Straight-line Type, and of course all disorders are labeled 'perceptive,' but diagnoses range over familial, toxic, and traumatic causes, while the audiograms show a great variety. Two have a high-tone loss sloping off 20 db per octave; one has a sharp drop of 50 db per half-

octave starting at 1500 cps; one has a 50 db dip at 2000 cps returning to normal symmetrically at 25 db per octave, and one has a saddle-shaped audiogram broadly through the speech range. No trends certainly are apparent here. Of course it remains logically possible that were one able to break down into finer categories the broad diagnostic phrases universally used in otology, one might be able to use the covariance of pitch and loudness, where it exists, to throw light upon the psycho-physioneurological nature of the ΔI and the ΔF, but at the moment the matter is in abeyance.

Does the Loudness-Memory ΔI Deteriorate with Increasing Interstimulus Interval?

Békésy (*1*) found the ΔI to deteriorate by about 20% when the interstimulus interval was increased from 0.25 sec to 5 sec. Postman (*76*) found little or no effect from 1-6 sec, though the 0 interval was very slightly better. Harris (*33*), for noise bursts, found no effect from 0 - 1 sec. Pollack's data (*74*) extend to 10 and 20 sec, with different variants of the $DL_{75\%}$; he found little if any reliable effect at any interval.

Two subsidiary problems are encountered in this firm fixing of an interval reference standard. One ancient problem is the time-error in judgments of successive stimuli, which would take us too far afield to discuss here; the other problem is the time lag of first response to a very slowly changing loudness. This problem has its own interests, being in essence an elementary sort of auditory tracking (*49*), but its relation to the classic measures of ΔI is not experimentally clear.

Neural Correlates of the ΔI

The neural mechanism of Loudness-Memory must be relatively uncomplicated, since the auditory cortex is not essential. Several workers from the Rochester laboratory (77, *82*) have shown that a cat can yield $DL_{inc\ 90\%}$ in db, for short tones varying between two intensity levels with 1.5 sec silent intervals, as fine without as with its auditory cortices. Furthermore, if the midbrain nuclei are destroyed in addition, the $DL_{inc\ 90\%}$ is deteriorated but by no means lost; here the ΔI is obviously being mediated by nuclei in the bulb.

An interesting comparison obtained between cat and man is from Raab and Ades (77); the mean $DL_{inc\ 90\%}$ for each of seven normal cats at 125, 1000, and 8000 cps, at about 60 db SL, was 2.9, 1.82, and 3.89 db respectively. The method used, moreover, does not exhaust the cat's discriminative ability. These data may be compared to the data for the groups of untrained S_s given a loudness-memory test in the present paper (Figure 11). Rosenzweig (*82*) with exactly the same procedure as Raab and Ades gives mean values of 2.0, 2.4, and 5.0 db for the same three frequencies for three cats, and adds the $DL_{75\%}$ for five young men given exactly the same stimulus pattern as his cats. The mean at 125 and also at 1000 cps was about 0.8 db, at 8000 cps about 1.5 db. Rosenzweig notes that the Riesz data would have predicted the threshold at 125 to be somewhat *larger* than at 1000 cps because the sensation level was less. He felt that some peculiarity in his stimulus conditions, perhaps undesirable standing waves, had intruded. However, we note that (a) at weaker

TABLE 13. JND$_{\text{inc}}$ in decibels for Loudness/Masking for one subject (data from Upton and Holway, *91*).

Exposure Time in Seconds		48			SPL 62			78	
	Left	Right	Binaural	Left	Right	Binaural	Left	Right	Binaural
1	3.2	4.2	1.9	3.9	2.9	2.5	4.6	4.3	3.1
3	2.2	2.5	1.4	2.3	2.1	2.1	3.0	2.5	2.5
10	1.5	1.8	1.0	1.9	2.0	1.7	1.9	1.6	1.5
20	1.3	1.6	.9	1.4	1.6	1.2	1.8	1.2	1.0
40	1.2	1.3	.9	1.3	1.2	1.1	1.0	.7	.7
90	1.1	1.0	.8	1.1	1.0	1.0	1.0	.8	.5
120	.9	1.0	.7	.8	.8	.8	1.0	.7	.4

sensation levels, 125 cps can still be *as loud as* a higher frequency, and (b) the loudness-memory paradigm yields data often unaffected by sensation level. It is probable that nothing was wrong with Rosenzweig's situation and that his data may be taken at face value.

The Influence of Binaural Hearing

The addition of the second ear can have effects depending upon the relations of the sounds in the two ears.

1. Same frequency, phase, and temporal patterns. In case the other ear hears an exact replica, there is definitely a slight improvement in the ΔI. Churcher, King, and Davies (*10*) showed with sine-wave amplitude modulation that the peak-to-peak JND improved from 2.56 to 2.12 db at 10 db SL and from 0.4 to 0.27 at 90 db SL. Intermediate SLs yielded comparable improvements. Upton and Holway (*91*) used a Loudness/Masking test and a variant of the method of limits. Their data, converted to JND$_{\text{inc}}$ in db, for a single observer are given in our Table 13. In this table the column headed Exposure Time indicates the duration of a continuous-tone adaptation period before judgments were begun.

(There is an apparent discrepancy between these figures and other data on the question of overall loudness and the ΔI. The exposure time, by perstimulatory fatigue, reduces the overall loudness, which, one would predict, should coarsen the ΔI. But in Table 13 it is seen that the exposure time regularly and quite markedly *improves* the ΔI. The reasons for this trend have never been explored.)

Table 13 shows for any particular loudness and exposure time that the binaural ΔI is often, though by no means always, better than the better ear alone. But the effect is never of the order of 3 db as demanded by Crozier's statistical theory, which would predict that the ΔI is related to the variance of the psychometric functions; if the variance is reduced by $\sqrt{2}$ as the result of doubling the number of neural inputs, the ΔI should likewise improve by a factor of $\sqrt{2}$, or 3 db.

(Aside from the fact that the data do not at all bear out Crozier's hypothesis, there seems to the writer a logical *hysteron proteron* in assuming the size of the ΔI to be a consequence of its variance. The two are certainly related, as the psychometric functions from
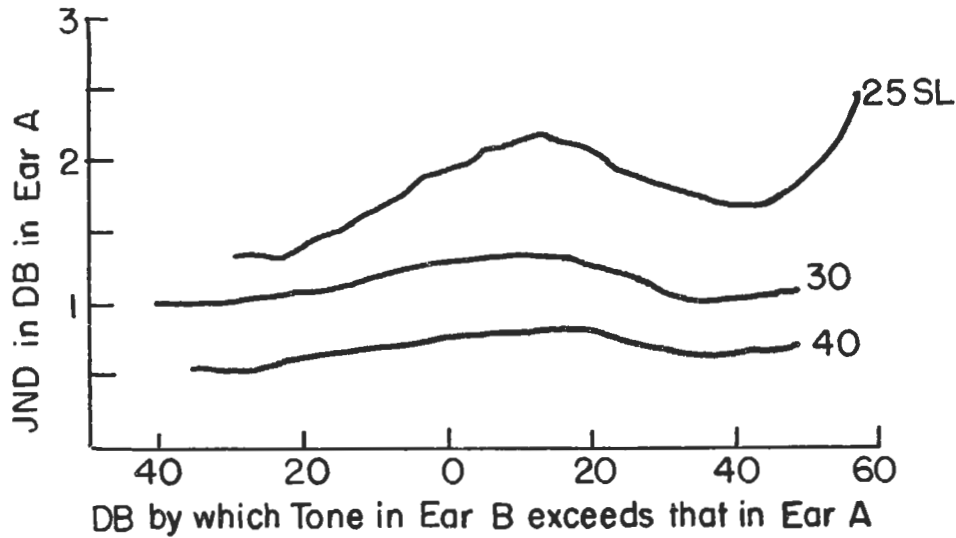
FIGURE 16. Effect upon JND of introducing a simultaneous tone in other ear. Data from reference *26*.

many laboratories will show [published most extensively by Chocholle]; but the causative order is not clear.)

From the scattered data which exist, it is not really possible to assess statistically whether binaural ΔIs are in reality superior to monaural ΔIs. A full study is still to be done equating overall loudnesses in one vs. both ears, randomizing experimental sessions, with more Ss and using all three types of loudness ΔIs. At the moment it seems to the writer that the difference, if any, would turn out to be a matter of less than 0.5 db.

2. A different stimulus in the second ear. Gage (*26*) shows that a steady-state tone in one ear can affect the JND for a 'clicky' alternation of intensity levels in the other ear. He used instantaneous intensity changes every 0.1 sec; S was required to adjust until a 'flicker' could just be heard. The data are rather curious, and the results at 800 cps are reproduced in our Figure

16. Note that when the intensity in the 'continuous' ear is much weaker, little effect on the JND is seen; but increasing the continuous intensity coarsens the JND up to a maximum when the continuous intensity is 10 to 15 db over that in the 'flickered' ear; whereupon it declines *and subsequently rises.* Gage states that these transitions are correlated with the Ss experience that the 'flicker' is located in one or the other ear. This whole experiment badly needs repetition with a more precise control and definition of stimulus complexity and phase. Most interesting results would certainly follow.

Chocholle (*9*) likewise applied a steady tone of the same frequency in the contralateral ear. His extensive data are compressed in our Figure 17. Note that the JNI is commonly inferior by a factor of 2-3 when the steady-state tone is raised to 60 db SL. Chocholle rejects peripheral masking and puts the braking action of the steady-state tone
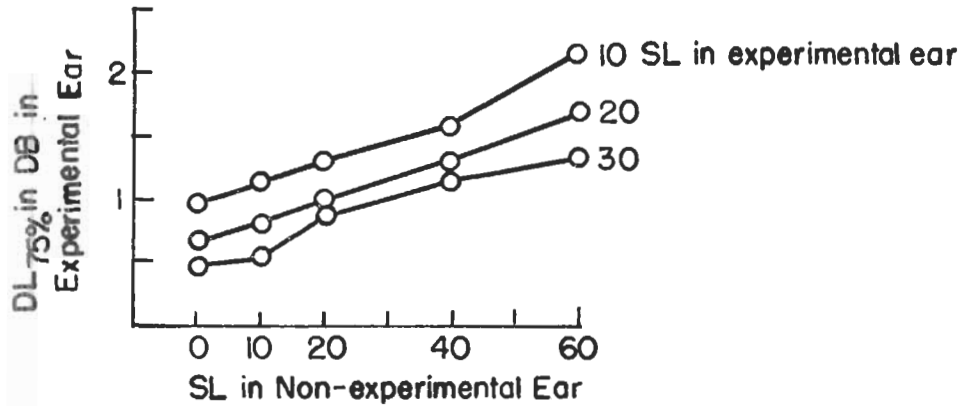
FIGURE 17. Effect upon ΔI of introducing a simultaneous tone in other ear. Data from reference 9.

in the cortex with the notions of (a) sensorial interference at the cortex level and (b) a reduced contrast between an increment and a higher background of sensory activity in the cortex. The writer finds the latter notion the more persuasive. It is at least agreed that the effect is not peripheral.

The ΔI and Physiological Noise

Pierce (68) has recently approached the explanation of the size of the ΔI, and its dependence upon overall loudness, by an elaboration of Stevens' notion that loudness changes are judged to a constant fraction K of the overall loudness—except for an uncertainty d introduced in some way, through added physiological noise or background fluctuation. Pierce makes the definite assumption that this noise is the momentary fluctuation in number of nerve impulses to a continuous sound. Coupled with the assumption that loudness is proportional to average number of impulses per second, Pierce constructs the equation

$$\Delta S = A^{-1/2} \, T^{-1/2} \, S^{-1/2}$$

where ΔS is ΔI in sones, A is a constant, T is the time of action of the stimulus, and S is the overall loudness in sones. For Riesz' experiment, where T was taken as 1/6 sec, the data at 1000 cps are fitted well by the above equation up to 70 db SL; furthermore, by rearranging the equation to show the relation between log overall loudness vs. the log of the sum of ΔIs at that loudness, Pierce again fits Riesz' data up to 70 db SL. The latter fit is, however, inferior to the fit of the equation generated by Stevens to the effect that loudness is equal to $KN^{2.2}$ where N is the number of ΔIs at that loudness.

A number of points bother the reviewer of Pierce's ingenious paper. It is a very persuasive and clever assumption that the limits of ΔI at any frequency and loudness are set by the inherent temporal fluctuation of nerve pulse rate, but the facts are that

(a) there is equally good reason to assume that number of active fibers is a closer correlate of loudness (of course, the noise could still be regarded as momentary fluctuations in this number); and, more telling,

(b) through wide ranges of overall loudness, where number of active fibers and also pulse rate must vary many-fold, all tests of Loudness-Memory agree that the DL does not change appreciably as does Riesz' data, and furthermore there is little or no effect of frequency. (In Pierce's formulation the constant A varies quite widely with frequency.)

Conclusions

There are at least three primary auditory abilities in loudness discrimination: Pure Tone Loudness-Memory, Loudness/Masking, and Loudness-Modulation. They may be distinguished in three ways: by mass tests, by the effects of frequency and overall loudness, and by differential effects in the oto-audiological clinic. No specific neurophysiological mechanisms can as yet be ascribed. Pure-Tone Loudness-Memory is affected most by forcing S to make choice 'louder'–'softer.' Under these conditions the $DL_{75\%}$ is of the order of 0.5 db, being quite unaffected by frequency changes from 125 to 6000 cps and by changes in phon levels up to 80 db. Loudness/Masking includes tests of noise-in-noise as well as of pure tones in a variety of noise backgrounds. It is strongly affected by overall loudness. Loudness-Modulation separates cleanly as a factor but is much better assessed with sine-wave modulation than with the 3-cycle frequency-beat stimulus complex. It too is strongly affected by overall loudness. Data on experienced and inexperienced listeners are provided on all of these tests, together with some parametric substudies.

No general excitation theory can be found specific enough to help understand the details of the data. It is not likely that the ΔI is related either to a constant amount of an excitatory substance nor to a neurophysiological constant such as a certain increment in number of active nerve fibers or in pulse rate. The writer feels it likely that loudness is related in some way to number of active fibers and that the ΔI is related to some sliding ratio of number of additional fibers activated by a stimulus increment. At weak loudnesses the ear needs in some cases an increase in loudness of over two-thirds before an additional just noticeable difference appears, while at 100 db sensation level a just noticeable difference is yielded by as little as 1% additional loudness.

An improvement in the loudness ΔI (as in a recruiting ear) does not necessarily have to be 'paid for' by a deterioration in the frequency ΔF.

The following conclusions arise not from the present experiments but from a literature survey:

1. A surprisingly good ΔI can be mediated by bulbar nuclei. Evidently loudness discrimination is a relatively uncomplicated operation.

2. The all-or-none principle introduces the logical possibility of a saltatory increase in loudness sensation, but this experience has in fact never been reported (it arises as an inference from computations) and the multiple innervation and convergence of the hair cell-neurone connections argue against a 'quantum' concept at any but the weakest loudnesses.

3. If a binaural input is matched in loudness to a monaural, it is likely that any improvement due to the addition of the second ear would be of the order of 0.5 db or less. On the other hand, if a steady tone is led to the non-experimental ear, the ΔI in the experimental ear will undergo some slight deterioration.

* * * *

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It is not possible for a paper such as this to come from the mind and work of a single individual. Persons too numerous to mention have had a small or a considerable part in working out this or that section of the whole. Especial acknowledgment can, however, be extended to those who contributed really original thought or who spent more than a few months in some phase or phases.

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The paper in its present form would have been impossible without this wholehearted cooperative effort. The writer is, however, to be held to account for errors of omission or commission in the overall program and for all interpretive material.

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