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F/G 6/19

TOWARDS A BETTER UNDERSTANDING OF TEMPORARY THRESHOLD SHIFT OF --ETC(U)

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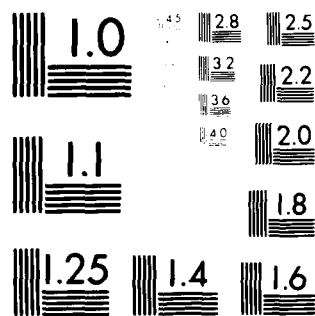
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ROYAL AIRCRAFT ESTABLISHMENT

Technical Memorandum FS 319

Received for printing 7 March 1980

TOWARDS A BETTER UNDERSTANDING OF TEMPORARY THRESHOLD SHIFT OF HEARING

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SUMMARY

It was thought that Temporary Threshold Shift of hearing due to exposure to noise might be more easily understood if the shifts were considered in terms of the rms pressure rather than in dB. Therefore, the forms to be expected if the rate of shift of the pressure threshold were proportional to the difference between itself and the ultimate threshold were calculated, and compared with a limited selection of published data. Good agreement with data for the growth of TTS in individuals was found, and moderately good agreement with recovery. Agreement with data on intermittent exposures was poor, but this may be due in part to the fact that only averaged data have been found, and averaging the widely disparate figures obtained for individuals may mask the true effects. It is also shown that the maximum ultimate TTS due to exposure to noise may be simply related to the mean square pressure of that noise.

Further consideration of the mass of published work is needed, but this study suggests that at least some facets of TTS can be simply described in terms of exponential pressure shifts.

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1 INTRODUCTION

There must by now be hundreds of published papers dealing with the phenomenon of temporary threshold shift (or TTS) due to exposure to noise. I cannot claim to have studied more than a small fraction of the literature, but from this an impression emerges that our knowledge of TTS consists of a collection of isolated pieces of information from which it is impossible to form coherent generalizations except in the broadest terms. I quote the salient points from a summary given by Ward¹ in 1968, but which still seems to contain the accepted facts.

"1. The growth of TTS in dB is nearly linear in the logarithm of time... . Moderate TTS also recovers exponentially in time, recovering completely within 16 hours. However, when TTS has reached 40 dB or more, recovery may become linear in time ... requiring days or even weeks to disappear.

2. Noise whose maximum energy is in low frequencies will produce less TTS than those whose energy is at high frequencies.

3. The maximum effect from noise ... in a narrow frequency range will be found half an octave to an octave above that range.

4. TTS increases linearly with the average noise level, beginning at about 80 dB, at least up to 130 dB or so.

5. In intermittent noise TTS is proportional to the fraction of the time that the noise is present. A noise that is only on half the time (in bursts of a minute or less) can be tolerated for more than twice the time that could be spent in the noise when continuous before the same TTS would be produced.

6. Neither growth nor recovery from TTS is influenced by drugs, medications, time of day, hypnosis, good thoughts or extra-sensory perception."

I am only concerned in this paper to consider items 1, 4 and 5 of this summary - those that deal with the process of growth of and recovery from TTS; and my object is to suggest an approach which may help to produce a more coherent picture. Threshold measurements are always difficult, and wide inter- and intra-subject variations are to be expected. This fact probably accounts for some part of the scatter and irregularity of published experimental results. But, even so, these exhibit a degree of inconsistency which demands further explanation.

I start from the first words of Item 1: "The growth of TTS in dB .."; and I ask: "Why should we measure TTS in dB?" The obvious answer is: "Because that is how our instrumentation works", to which may be added: "Because that is how we hear the loudness of noise." But are these sufficient reasons? TTS must be basically due to physical or possibly chemical causes which could produce effects such as the softening of a part of the hearing mechanism that functions as a spring, or relative movement of two parts due to differential heating, which might lead to a variation in threshold. These effects could be exponential, but it seems far more likely that they would produce a shift of the threshold rms pressure, than of the *logarithm* of that pressure (the dB shift).

This paper sets out to answer, by simple analysis, the question: "If in fact the rms pressure at threshold is subject to a simple exponential shift (see section 2) due to exposure to noise, how would that shift appear if measured in dB?" For the most part, only the simplest case is considered. Curves for growth and recovery are shown, plotted against normalized linear and logarithmic time scales, so that the forms can be recognized at sight. The time constants which might be deduced from these curves are discussed, and the effects of averaging are considered - since in much published work only averages are given. The effects of intermittent exposures following these rules are analysed, and possible mechanisms governing the final or asymptotic threshold shift are described.

In comparing the calculations with published work, some pronounced disagreement was observed, specifically in dealing with intermittent noise; but on the whole agreement was good. It is probable that the simple forms studied here would need elaboration to deal with all the dynamic aspects of TTS; but a start has been made. This is sufficient to suggest that understanding TTS, and possibly other acoustic phenomena, might be facilitated by making experimental measurements in pressure rather than in dB. Whether this is a practical proposition when we are conditioned to use dB, and when all our measuring equipment operates in dB, is doubtful; but it would be a hopeful step if we could stop ourselves always, automatically, thinking in dB.

2 ANALYSIS

In the analysis given in this section, it is assumed throughout that the rate of change of the rms pressure at threshold in steady noise is proportional to the difference between that pressure and the ultimate, or asymptotic rms pressure at threshold. Thus, whether in growth or recovery, the threshold will

always tend exponentially to an ultimate value if the noise conditions are steady. This kind of variation with time occurs when there is a step change in the forcing function applied to a first order, one-degree-of-freedom system, and is common in nature in other connexions than acoustics: for example, the variation of the voltage on the condenser in an RC circuit for a step change of the voltage across the circuit, or the variation of the temperature of a body subject to Newtonian cooling for a step change of the power supplied or of ambient temperature. Details of the analysis are given in Appendices A, B and C.

2.1 Steady noise

2.1.1 Growth and recovery

p_1 Pascal rms is the threshold pressure at a particular frequency before exposure to noise

p_2 Pascal rms is the ultimate threshold pressure at the same frequency for continuous exposure to a particular kind of noise

p Pascal rms is the threshold pressure at the same frequency at time t minutes from the beginning of the exposure

T minutes is the exponential time constant.

(During recovery, p_2 is the initial threshold and p_1 the ultimate threshold.)
Then

$D' = 20 \log(p_2/p_1)$ is the ultimate threshold in dB,
and $D = 20 \log(p/p_1)$ is the threshold in dB at time t .

It is clear that D' must depend on the noise level to which the ear is exposed; but the nature of this dependence will not be considered in this section.

The forms for exponential growth and recovery, that is, the solution of the equation $dp/dt = \text{constant} \times (p_2 - p)$, are given in many elementary textbooks.

In growth:

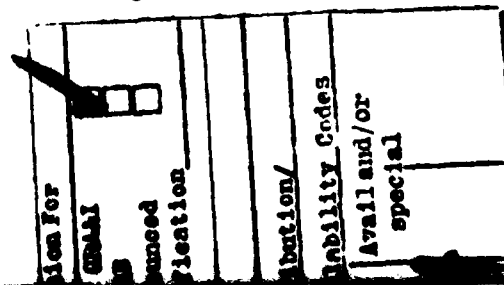
$$(p - p_1) = (p_2 - p_1)[1 - \exp(-t/T)] \quad (1)$$

or

$$(p/p_1) - 1 = [(p_2/p_1) - 1][1 - \exp(-t/T)] .$$

Taking logarithms and substituting antilog $(D'/20)$ for (p_2/p_1) , we have

$$20 \log(p/p_1) = D = 20 \log\{1 + [1 - \exp(-t/T)][\text{antilog}(D'/20) - 1]\} . \quad (2)$$



In recovery:

$$(p_1 - p) = (p_1 - p_2) [1 - \exp(-t/T)] \quad (3)$$

or

$$(p/p_2) - 1 = [(p_1/p_2) - 1] \exp(-t/T)$$

whence

$$20 \log(p/p_2) = D = 20 \log\{1 + \exp(-t/T) [\text{antilog}(D'/20) - 1]\}. \quad (4)$$

Fig 1a&b show the usual exponential growth and recovery curves given by equations (1) and (3) plotted against the normalized time (t/T) on linear scales. Fig 1c&d show the same equations plotted against logarithmic time scales. Fig 2a&b show the growth and recovery of the dB level D from equations (2) and (4) against (t/T) on linear scales, for values of D' from 10 to 60. Fig 2c&d show the corresponding plots on logarithmic scales for (t/T) .

2.1.2 Derivation of time constants

The same symbols as in section 2.1.1 are used, and additionally:

T' minutes denotes an apparent time constant

D_T dB is the threshold at time $t = T$.

In this section we shall discuss the time constants which might be derived from dB plots such as those shown in Fig 2. All the methods described have been used by some experimenters.

(a) For a true exponential form as illustrated in Fig 1, the time constant is that time at which

$$(p - p_1) = (p_2 - p_1) [1 - \exp(-1)] \quad \text{in growth}$$

or

$$(p - p_2) = (p_1 - p_2) \exp(-1) \quad \text{in recovery}$$

as shown by the dashed lines in Fig 1.

If, therefore, it is assumed that the dB threshold is a truly exponential function of time, a time constant may be derived from plots on either linear or logarithmic time scales by taking the time at which

$$\left. \begin{array}{ll} D = D' [1 - (1/e)] & \text{in growth} \\ D = D'/e & \text{in recovery} \end{array} \right\} \quad (5)$$

It will easily be seen that these two forms are identical if we refer to the initial conditions in both growth and recovery, and use a negative value for D' in recovery. Thus we have a continuous function connecting T' and D' by combining equations (2) and (5), to give

$$20 \log\{1 + [1 - \exp(-T'/T)][\text{antilog}(D'/20) - 1]\} = D'[1 - (1/e)] \quad (6)$$

which gives

$$(T'/T) = \ln[1 - \text{antilog}(-D'/20)] - \ln[1 - \text{antilog}(-D'/20e)] . \quad (7)$$

Fig 3 shows (T'/T) plotted against D' (full line) from equation (7).

Conversely, it is interesting to consider the actual shifts in dB after a time lapse equal to the true time constant, that is, by putting $t = T$ in equation (2). It is clear that if D' is large and positive, the term in $\text{antilog}(D'/20)$ is large compared with unity, so that

$$D_T \cong 20 \log\{[1 - (1/e)] \text{antilog}(D'/20)\} = D' - 20 \log[e/(e - 1)] = D' - 3.98 . \quad \dots\dots(8)$$

Also, if D' is large and negative, the term in $\text{antilog}(D'/20)$ may be neglected, so that

$$D_T \cong 20 \log(1/e) = -8.68 . \quad (9)$$

Fig 4 shows a plot of D_T against D' , together with the lines given by equations (8) and (9).

(b) Again, with a true exponential plotted against a linear time scale, the tangent at the origin reaches the ultimate value at time T , as shown by the dotted lines in Fig 1a&b.

Hence, if the dB plot against linear time were assumed to be a true exponential, the same procedure might be applied. We can show (see Appendix A) that the tangent at the origin to the dB/linear-time plot is given by

$$D = (t/T)(20/\ln 10)[\text{antilog}(D'/20) - 1]$$

which meets $D = D'$ where $t = T'$, the apparent time constant, given by

$$(T'/T) = D' \ln 10 / \{20 [\text{antilog}(D'/20) - 1]\} . \quad (10)$$

As in case (a), this expression can be used in recovery as well as growth, to give the form shown in the dashed curve in Fig 3.

(c) A glance at Fig 2c&d shows that it is impossible to draw conclusions from tangents at the origin in logarithmic plots. The origin cannot be plotted on a log scale, and if a time shortly after the beginning of growth or recovery were taken, the slope of the tangent is still very small and almost meaningless. But some experimenters have taken the tangent at the steepest part of the curve and considered its intercept with $D = D'$ as giving the time constant. This line is effectively the tangent at the point of inflexion of the curve, and it can be shown (see Appendix B) that this tangent meets $D = D'$ at a time T' given by

$$(T'/T) = x_1^z \quad (11)$$

where $z = x_1 / (x_1 - 1)$ and $20 \log [1 + (x_1 - 1) \exp(x_1)] = -D'$.

As before, these expressions hold both for growth and recovery. A plot of (T'/T) against D' obtained by varying x_1 from 0.044 ($D' = 60$) to 5.43 ($D' = -60$) is shown in the dotted line in Fig 3. It might be argued that it would be more appropriate to take the time between the intersections with the initial and final thresholds as the time constant. If this were done, we should have (see Appendix B) with x_1 and z defined as before

$$(T''/T) = x_1^z \left\{ 1 - [1 + (x_1 - 1) \exp(x_1)]^{1-z} \right\} . \quad (12)$$

If plotted in Fig 3, equation (12) would give a curve indistinguishable from the dotted curve for positive values of D' , but diverging for negative values of D' to be about 20% lower when $D' = -60$.

2.1.3 Some effects of averaging

It is clear (see, eg Ref 2) that the TTS produced in individuals by exposure to the same noise may vary widely both in magnitude and in the rate of response. The effects of arithmetic averaging of dB shifts in some simple - and by no means extreme cases - on the apparent response and on the estimated time constants will be considered in this section.

Fig 5 shows, with the same arrangement as in Figs 1 and 2, growth and recovery for a shift to 30 dB, full line, the average for shifts to 20 and 40 dB (dashed line) and the average for shifts to 10 and 50 dB (dotted line) all having the same time constants. The time constant ratio read off these curves by the methods (a), (b) and (c) of section 2.1.2 are approximately as given in Table 1 below.

Table 1

(T'/T) from averaged shifts with the same time constant

Method Shifts	Growth			Recovery		
	a	b	c	a	b	c
30 dB	0.30	0.12	1.5	2.5	3.5	5.0
20 dB and 40 dB	0.29	0.10	1.5	2.7	3.8	5.6
10 dB and 50 dB	0.20	0.05	1.9	3.6	4.3	6.5

The second case, illustrated in Fig 6, is for the results for two individuals having the same shift but different time constants T_1 and T_2 . The results are shown plotted against the time relative to the mean time constant $T = (T_1 + T_2)/2$, and the ratios of the time constants are 1 (clearly the simple case shown in Figs 2), 3, 9 and 27. The time constants, relative to the mean time constant T which would be deduced from these curves are approximately as given in Table 2 below.

Table 2

(T'/T) from averaged shifts with different time constants but the same ultimate shift

Method T_1/T_2 T_1/T T_2/T			Growth			Recovery		
			a	b	c	a	b	c
1	1	1	0.30	0.12	1.5	2.5	3.5	5.0
3	1.5	0.5	0.28	0.11	1.5	2.15	2.8	5.3
9	1.8	0.2	0.20	0.10	1.3	1.95	1.3	4.6*
27	1.93	0.07	0.14	0.08	1.5	1.9	0.6	2.3*

* from the first steep decline

2.2 Regular intermittent exposures

Suppose the ear is exposed alternately to noises of the same kind but different levels which would, if continuous, ultimately produce shifts to p_2 and p_2' Pascal rms, or D' and D'' dB.

x_{2n-1} and x_{2n} are the threshold pressures and D_{2n-1} and D_{2n} are the dB thresholds after the n th exposures to the first and second noises respectively.

If the period of exposure to the first noise is t_1 minutes, and to the second noise is qt_1 minutes, let $y = \exp(-t_1/T)$. Then it can be shown (see Appendix C) that for exponential growth (or recovery) during each exposure,

$$x_{2n} = p_1 y^{n(q+1)} + \left[p_2(1-y)y^q + p_2'(1-y^q) \right] \left[1 - y^{n(q+1)} \right] / \left[1 - y^{(q+1)} \right]. \quad (13)$$

Ultimately, after very long periods, the terms involving y^n may be neglected since y is always less than unity, hence

$$x_{2n} \rightarrow \left[p_2 y^q(1-y) + p_2'(1-y^q) \right] / \left[1 - y^{(q+1)} \right]. \quad (14)$$

Then, if (t_1/T) is large, y is small, so that $x_{2n} \rightarrow p_2'$, as might be expected.

On the other hand, if (t_1/T) is small, y is close to unity, and

$$x_{2n} \rightarrow (p_2 + p_2'q)/(1+q) \quad (15)$$

or, in dB

$$D_{2n} \rightarrow 20 \log \{ [\text{antilog}(D'/20) + q \text{ antilog}(D''/20)] / (1+q) \}. \quad (16)$$

If the first noise is effectively quiet, $p_2 = p_1$, and

$$D_{2n} \rightarrow 20 \log \{ [1 + q \text{ antilog}(D''/20)] / (1+q) \}. \quad (17)$$

If the periods of exposure are not short, so that terms in y may not be neglected, we can select the special case where periods of quiet alternate with equal periods of noise. Then, from equation (14), we have

$$x_{2n} \rightarrow (p_1 y + p_2') / (y + 1).$$

Then if (p_2'/p_1) is large compared with y ,

$$D_{2n} \rightarrow D'' - 20 \log(1 + y) . \quad (18)$$

The particular case of short exposures to noise alternating with short periods of quiet, as in equation (17), is illustrated in Fig 7, where the limit of D_{2n} is plotted against the exposure ratio $k = q/(1 + q)$.

2.3 Complex responses

The analysis so far has dealt only with the case where TTS is due to one mechanism having a fixed time constant and a known relationship between the ultimate shift and the intensity of the noise. But study of published results suggest that this may often be too simple a model. We know, for instance, that noise exposure may produce tinnitus, which will produce an apparent TTS by masking the threshold at some frequencies - but a genuine shift may be present at those frequencies at the same time. In this case if the two effects are in series, the apparent TTS will be due to the greater of the tinnitus-masked threshold and the actual threshold. Conversely, if the effects are in parallel, as for instance if the two ears of an individual respond differently and the threshold for the individual be measured in free field, the measured threshold shift would be the lower of the two shifts. But this situation, though common enough in real life, is rare in experiments, and will not be considered further.

Among many possible combinations, we shall consider only one, that in which there are two responses with different time constants and with ultimate shifts dependent on the noise exposure according to different laws. In this analysis it will be assumed that the rms threshold pressure shifts are proportional either to the rms pressure of the noise, or to its square.

2.3.1 Variation of ultimate TTS with noise level (linear or square law)

Let the noise level be L dB, where $L = 20 \log(P/p_r)$, p_r being the reference pressure $20 \mu\text{Pa}$. Suppose then that the ultimate threshold pressure shift is proportional to the n th power of P , that is

$$p_2 - p_1 = AP^n ,$$

where A is a constant

hence

$$D'_n = 20 \log(p_2/p_1) = 20 \log\{1 + A' \text{antilog}(nL/20)\}$$

where $A' = A/(p_1 p_r^n)$,

which may be written

$$D'_n = 20 \log\{1 + \text{antilog}[n(L - C)/20]\} \quad (19)$$

where C is a constant equal to $-(20/n) \log A'$.

For a linear relationship $n = 1$, and for a square law $n = 2$, so substituting in equation (19) we have

$$\left. \begin{array}{l} \text{the linear law: } D'_1 = 20 \log\{1 + \text{antilog}[(L - C_1)/20]\} \\ \text{and} \\ \text{the square law: } D'_2 = 20 \log\{1 + \text{antilog}[(L - C_2)/10]\} \end{array} \right\} \quad (20)$$

Fig 8 shows the form of D'_1 and D'_2 for various values of the parameters C_1 and C_2 .

It may be noted that $D'_1 = D'_2$ when $L = 2C_2 - C_1$. Thus for smaller values of L , the linear law governs the ultimate shift, and for larger values of L , the square law, if the two mechanisms are in series.

2.3.2 Growth and recovery when both linear and square law operate

The forms for growth and recovery when we have a linear law with the constant C_1 and time constant T_1 and a square law with the constant C_2 and time constant T_2 is given by substituting from equation (20) in equations (2) and (4), and in each case plotting the maximum value. Thus in growth, the threshold will be the greater of D_1 and D_2 where

$$\left. \begin{array}{l} D_1 = 20 \log\{1 + [1 - \exp(-t/T_1)] \text{antilog}[(L - C_1)/20]\} \\ D_2 = 20 \log\{1 + [1 - \exp(-t/T_2)] \text{antilog}[(L - C_2)/10]\} \end{array} \right\} \quad (21)$$

and in recovery, the threshold will be the greater of

$$\left. \begin{array}{l} D_1 = 20 \log\{1 + \exp(-T/T_1) \text{antilog}[(L - C_1)/20]\} \\ D_2 = 20 \log\{1 + \exp(-T/T_2) \text{antilog}[(L - C_2)/10]\} \end{array} \right\} \quad (22)$$

Fig 9 shows the forms for the particular case where $T_2 = 10T_1$, $C_1 = 60$ and $C_2 = 70$, for values of L from 70 to 100.

3 DISCUSSION

Before discussing the analytical results in detail, we shall first (in section 3.1) see how far the forms illustrated in Figs 2, 5, 6 and 9 are consistent with the general summary quoted in the Introduction, and second (in section 3.2) discuss some of the problems involved in measuring temporary threshold shift.

3.1 Comparison with Ward's summary (see Introduction)

The analysis given in section 2 can relate only to items 1, 4 and 5 of the summary.

Item 1: Fig 2c shows that for reasonably large ultimate shifts "the growth of TTS in dB is nearly linear in the logarithm of time" for the exponential growth of rms pressure at threshold - that is, until the ultimate level is approached. Also, "moderate TTS" *does* "recover exponentially" under the exponential pressure rule, as shown by Fig 2b&d - though they do *not* show that TTS "recovers completely" at any time, since complete recovery is impossible in any asymptotic process. "When TTS has reached 40 dB or more, recovery may become linear in time, requiring days or even weeks to disappear"? Again, it can never completely disappear, but Fig 2b certainly shows recovery very nearly linear with time for large TTS, or, from Fig 2d, after an initial period of apparently slow recovery, TTS does vary nearly linearly with the logarithm of time until the ultimate level is approached.

Item 2 "TTS increases linearly with the average noise level." The curves of Fig 8 show that for moderately large values of TTS either the linear or square law would give rise to approximately linear relationships, having regard to experimental error and the general paucity of data points. This does not show, of course, that either of the laws holds, only that neither is incompatible with the statement of Item 2.

Item 5 "TTS is proportional to the fraction of the time that the noise is present" so long as the noise comes "in bursts of a minute or less". Here we may refer to Fig 7, which shows that TTS could be taken as linear with the exposure ratio for small values of ultimate shift under the same noise uninterrupted, say up to about 20 dB; but above this level the curves are definitely nonlinear. Also, the analysis shows that if the exponential pressure law holds, a noise that

is only on half the time will *never* produce the same TTS as the continuous noise. Ward's assumption appears to be that it will merely take longer to reach that level, and this cannot be true under the exponential pressure law.

On the whole, however, it seems that the exponential pressure form does not contradict the basic ideas about TTS which are generally accepted. It remains to consider the implications of the analysis, and to compare the forms with some published results. But before such comparisons are instituted, it is as well to consider the probable sources of error inherent in threshold measurements, and also the effects that may be introduced by averaging.

3.2 Errors in measurement of TTS

As already mentioned (section 1), measurements of hearing thresholds are notoriously difficult to make with accuracy. They must always be interpolations between the level at which the subject definitely cannot hear the signal and the level at which he definitely can. With trained and practised subjects the difference between the levels may be as little as 5 dB, though 10 dB is probably more common. In addition, it is well-known that threshold levels at low frequencies may be masked by physiological noise, and at many frequencies by tinnitus (which may sometimes be caused by exposure to noise). These effects are probably more important when the test signal is presented at the ear in some kind of ear-muff, than when the signal is presented in free field.

Threshold measurements must be taken in quiet surroundings, so that, if we wish to measure the growth of shift during an exposure, the exposure is necessarily interrupted for at least a few minutes, and it is necessary to allow for this in assessing the duration of the exposure. Alternatively, measurements may be made at the conclusion of the exposure only; but this clearly involves a long and tedious process if several points on the growth curve are to be obtained, since recovery must be nearly complete before it is possible to reproduce the growth pattern. Hence, in addition to the errors probable in any threshold measurements, there are further sources of error in measuring TTS so that, for an individual ear errors of the order of 5 dB are probable. Since it is considered unethical to produce shifts exceeding 30 dB, the probable errors are of the order of one sixth of the maximum (in dB) and frequently a much larger proportion.

To eliminate at least some of the probable error, it is customary to average results for several subjects, and sometimes for several tests frequencies. But we have shown (section 2.1.3) that if TTS is governed by any exponential pressure law, comparatively small variations between individual results may mask

the nature of the shift, as shown by the analysis of Tables 1 and 2. On the whole, those averaged results suggest that there is likely to be more consistency about averaged growth data than about averaged recovery data. It will be seen later (section 3.3.1) that the range averaged in the examples is less than has been found by at least one experimenter.

The majority of papers on TTS report averages only. Some of these will be considered later; but of more interest are the individual results to be reviewed in the next section.

3.3 Comparison of analytical forms with published data on growth and recovery of TTS

Much of the data considered here has been derived from published graphs and is re-plotted in Figs 10 to 15 in forms similar to Fig 2. This assists comparison, but there is inevitably some copying error.

3.3.1 Individual ears

In the text-book Noise and Man² two sets of individual data are recorded, one from Mills *et al*³ the other from Ward *et al*⁴. In addition, Barry⁵ gives some results on his own right ear. These data are reproduced in Figs 10, 11 and 12 respectively.

In Fig 10 we have data on TTS at 750 Hz for an individual exposed to an octave band of noise centred at 500 Hz and at levels of 81.5 and 92.5 dB *re* 20 μ Pa, for periods up to 2 days, and for subsequent recovery over a period of a week. The curves have been drawn using equations (2) and (4), assuming a time constant of 390 minutes in each case, and ultimate shifts of 10 and 28 dB. It will be seen that the curves fit the growth data very well. The fit to the recovery data is less good - there seems to be a tendency to a flatter type of recovery curve - nevertheless, none of the measured thresholds is more than about 5 dB from the recovery curves.

In Fig 11a we have data on the recovery of the 12 ears of six subjects from the TTS at 3 kHz induced by exposure for 6 hours to intermittent noise in the frequency range 1.4 to 2 kHz. This graph is slightly simplified, in that where two or more curves lay within about 1 dB all the time, only one curve has been drawn (see Table 3 below). In Fig 11b we have curves constructed from equation (4) to fit the experimental results using the values for time constants and initial shifts given in Table 3. It will be noted that in three cases, curves 2, 5 and 6, it was necessary to postulate a double exponential in order to obtain a reasonable fit. No attempt was made to fit curves to the smallest shifts, since these

seemed very erratic, and there are no data between the 2nd and 15th minutes when most of the recovery must have taken place.

Table 3
Key to Fig 11

Subject	Ear	Curve	D_1^V (dB)	T_1 (min)	D_2^V (dB)	T_2 (min)
W	L	1	37	1200		
	R	5	17	30	10	330
A	L	2	36	100	32	670
	R	5	17	30	10	330
N	L	3	30	400		
	R	3	30	400		
B	L	4	18	500		
	R	4	18	500		
D	L	6	14	5	6	100
	R	8	-	-		
U	L	7	-	-		
	R	5	17	30	10	330

It is interesting to note that for only two of these six subjects is the recovery of the two ears similar.

Comparison of Fig 11a&b shows that the analytic curves fit the data fairly well, the most marked difference being for curves 2 and 3. These analytic curves approach zero more rapidly than the experimental curves, suggesting that there may be another mechanism causing slower recovery at low shifts.

The wide variation in Fig 11 suggests very strongly that such results, so disparate in magnitude and form, cannot be averaged and retain any meaning.

Fig 12 gives the growth and recovery (from Ref 5) at 707 Hz during and after exposure to an octave band of noise centred at 500 Hz at levels of 95 dB and 90 dB re 20 μ Pa, and at 2828 Hz on and after exposure to an octave band of noise centred at 2 kHz 85 dB and 80 dB re 20 μ Pa. The recovery data at 2828 Hz led in the original plots to final thresholds of about -3 dB, but, since the final TTS in growth was about 3 dB below that measured somewhat earlier, as can be seen in Fig 12a, it seemed reasonable to raise all the recovery measurements at 2828 Hz by 3 dB, and that is how the data are plotted in Fig 12b. The curves in Fig 12 were constructed from equations (2) and (4), using the constants given in Table 4 below.

Table 4
Key to Fig 12

Test frequency (Hz)	Exp. level (dB)	Growth				Recovery	
		D' ₁ (dB)	T ₁ (min)	D' ₂ (dB)	T ₂ (min)	D' (dB)	T (min)
707	95	20	85	30	500	30	500
	90	21	85			21	500
2828	85	14	400			14	400
	80	9	400			9	400

It will be noticed that a double exponential was needed to fit the growth curve at the higher level of exposure at 707 Hz. Inspection of Fig 12 shows that again the fit during growth is better than for recovery, and once again there seems to be a tendency for some other mechanism to take over in the final stages of recovery.

Barry⁵ also gives plots for one other subject for growth of and recovery from TTS at 2828 Hz. The growth data show a maximum shift of 19 dB at 2 hours, and there is one data point earlier than this: 10.5 dB at 1 hour. It is impossible to fit an exponential pressure curve to these points; but, since errors of at least the order of 2 dB are possible, this does not show that the shift is not an exponential pressure form. The recovery for this subject shows a very nearly linear decline against log time, and Barry states that all the subjects produced similar forms at 2828 Hz, as in the example shown in Fig 12b.

On the whole then, it has been found that growth patterns for individual ears can be fitted with exponential forms either simple or double. The fits to recovery data are not quite so good, though still reasonable except in the final stages and for very small shifts. The time constants found range from 5 minutes to 1200 minutes, but are mostly in the neighbourhood of 400 minutes. There is some indication that very small shifts may have very long time constants, and this effect would show up much more in recovery than in growth where the more rapid shifts would mask it. This is apparent from the analytic curves of Fig 9, where it can be seen that the growth curves are dominated by the shorter time constant and the recovery curves by the longer one. In particular, it can be seen that where both mechanisms lead to the same ultimate shift (as in the shift to 21 dB in Fig 9), the growth curve is simply that for the shorter time constant, and the recovery curve is that for the longer time constant.

3.3.2 Averaged data for growth and recovery

Most general papers and textbooks on TTS cite some one or other of sets of curves given by Ward at different times and in different connections for growth and recovery against logarithmic time scales. Burns² gives, from Ref 6, the sets of straight lines shown in Fig 13a. These show the averaged TTS at 4 kHz for the two ears of 13 men, 2 minutes after exposure to noise in the band 1200-2400 Hz at difference levels, as marked on the lines, for four periods lasting up to 100 minutes. Only the lines are shown in Fig 13a, but they are very good fits to the points. If we compare these lines with Fig 2c, it is easy to see that exponential forms could give rise to lines similar to these, assuming a time constant of about 300 minutes, and ultimate shifts for the four exposures of about 29, 37, 45 and 52 dB. In recovery, the lines shown in Fig 13b are nothing like the curves of Fig 2d. For a time constant of 300 minutes one would expect hardly any recovery at all in 100 minutes, certainly not more than about 3 dB whatever the initial threshold. But if we have wide variation, although individual ears may show exponential recovery from varying levels and with different time constants, the averages over fairly short periods may appear linear. The curves shown in Fig 11a, for instance, will give an average straight line on the log time scale up to 100 minutes. Hence, though the lines in Fig 13b cannot be said to support the exponential theory, neither do they entirely confute it.

Among other experimenters who have discussed time constants, Mosko and Fletcher⁷ present median data for 17 subjects exposed to noise with a flat spectrum up to 250 Hz, and falling off at 10 dB/octave above this frequency. The OASPL was 103 dB re 20 μ Pa, and exposure lasted 48 hours. Exponential curves of the forms

$$TTS_t = D' [1 - \exp(-t/T)] \quad (23)$$

$$TTS_t = D' \exp(-t/T) \quad (24)$$

were fitted by a least-squares process to the growth and recovery data in dB, respectively, to the data for the two test frequencies where the shift was moderately large. The results are given in columns (c) and (d) of Table 5 below. It will be seen that there is a wide range of time constant, and that the variation conforms to the exponential pressure shift theory in that the apparent time constants in recovery are greater than those measured in growth.

Table 5

Time constants for growth and recovery (from Ref 7)

Test frequency (Hz)	D' (dB)	Time constants (minutes)			
		Given in Ref 7		Modified by curve (a) Fig 3	
		Growth	Recovery	Growth	Recovery
(a)	(b)	(c)	(d)	(e)	(f)
500	13	301	495	500	265
2000	15	147	630	260	295

Fitting equation (23) or (24) to the data to determine the time constant is similar to method (a) of section 2.2.1, illustrated by curve (a) of Fig 3. Thus if the shift is governed by the exponential pressure law, the true time constant can be determined from the figures in columns (c) and (d) by dividing these by the ordinate for the positive or negative ultimate shift of curve (a) in Fig 3. The values so obtained are given in columns (e) and (f) of Table 5. It will be seen that, apart from the data for growth of TTS at 500 Hz, the results suggest a time constant of about 250-300 minutes. This treatment has therefore produced somewhat more homogeneous results than the original treatment, and the agreement with the exponential pressure shift theory for a single time constant, is quite as good as could be expected from averaged results.

Barry's averaged data for the right ears of five subjects are mainly given in the form of the equations to linear approximations to parts of the curves; but he gives plots for growth and recovery at 707 Hz and 2828 Hz. Recovery at 2828 Hz shows a linear decline against log time, as already mentioned in section 3.3.1, but the other plots show a superficial resemblance to the curves of Fig 2c&d. However, on closer investigation exact matching turns out to be impossible. Barry's figures are summarized in Table 6 below.

Table 6

Linear approximations to average data (after Barry⁵)

Test frequency (Hz)	Shift (dB)	A	B	C	D	E	F	A'	E'
(a)	(b)	(c)	(d)	(e)	(f)	(g)	(h)	(i)	(j)
500	10.5	4.6	5.69	-2.3	7.96	-5.5	11.13	7.5	-10.3
707	16.7	7.3	8.81	-1.5	14.83	-9.1	18.20	10.7	-17.8
1000	13.8	6.0	7.13	-3.1	10.56	-9.5	16.23	9.4	-14.1
2000	4.5	7.7	-1.13	-	-	-1.8	1.64	3.6	-4.0
2828	11.3	7.5	5.12	-	-	-3.5	4.56	8.0	-11.2
4000	7.7	10.7	0.80	-	-	-2.2	2.37	5.8	-7.3

In growth, Barry gives approximations of the form $TTS_t = A \log t + B$, for the steep region of growth, as given in columns (c) and (d) of Table 6. It is clear that this line should be close to (though probably slightly less steep than) the tangent at the point of inflexion given by equation (B-6) of Appendix B, but this slope is dependent on the ultimate shift D' given in column (b). The value of A corresponding to D' is given in column (i); and it will be seen that the correlation between Barry's results and equation (B-6) is not generally good. For example, at 707 Hz D' is 16.7 and A is 7.3, but the slope corresponding to this ultimate shift is about 10.7. Since the first data points are at 1 hour, when about half the growth (in dB) has already occurred, we should expect the slopes to be somewhat lower than those of the inflexion tangent, which may account for some part of the difference. Also, we have shown that averaging probably tends to reduce the slope. Hence, the averages for growth are not necessarily inconsistent with the exponential pressure theory.

For recovery, Barry gives approximations for an initial slow recovery, of the form

$$TTS_t = C \log t + d,$$

followed by a steeper recovery

$$TTS_t = E \log t + F$$

at the lower test frequencies; but he gives only one approximation for the higher test frequencies. The constants for C, D, E, F are given in Table 6, columns (e) to (h).

The slope E' of the inflexional tangent corresponding to the initial TTS (which would be expected to be approximately the same as E) is given in column (j).

Again it will be seen that the agreement is poor. Nevertheless, the effects of averaging might be sufficient to account for the discrepancies at low frequencies. The high frequency results are more difficult to reconcile with the exponential pressure theory.

The last paper which will be discussed in this section deals only with averaged results and purports to define TTS in terms of exponentials. Mills *et al*⁸ assert that the growth of TTS in dB can be expressed as a simple exponential function with time constant 2.1 hours, and recovery as a simple exponential function with time constant 7.1 hours. (That is what it says in the

summary - in the text the figures are 2 and 7.2 respectively.) This is said to hold so long as the ultimate shift does not exceed 30 dB. The statement is equivalent to equations (23) and (24), with $T = 2$ in growth and $T = 7.2$ in recovery.

The assertion is illustrated by a picture with numerous experimental points from various sources marked on it. This is reproduced in Fig 14, except that the experimental points are not entered only, the bands within which they lie are marked in with dashed lines.

Now quite clearly, these curves are not exponentials - if they were they would look like Fig 1a&b, and certainly they could not cross the time axis as the growth curve does near the origin and the recovery curve does at about 25 hours. The only points in which they agree with exponentials are in the final conditions in growth and the initial conditions in recovery, and in the points at which $t = T$ on both curves. What the actual equations of the curves are I have not been able to determine, if indeed they have analytic forms and are not simply free-hand drawings through two points! However, if we consider the actual values quoted for the time constants and compare them with the average values to be expected for shifts from say 5 dB to 30 dB, we find, using curve (a) of Fig 3, that in growth the average time constant will appear to be about 0.53 times the true time constant, and in recovery about 1.8 times the true time constant. Hence the values of 2 and 7.2 for T' in growth and recovery, lead to estimates of about 3.8 and 4 hours respectively for T . Thus, in this respect, the agreement with the exponential pressure theory is quite good.

3.4 Comparison with published data for the variation of ultimate shifts with the noise level

3.4.1 Results for individual ears

No data for individual ears has so far been found except that already cited in section 3.3.1 from Mills *et al*³ and Barry⁵. These data are reproduced in columns (a) to (e) of Table 7 below.

In each case we have only two points from which the apparent exponent, the slope of the line joining them, may be calculated, as shown in column (f) of Table 7. On the other hand, if we assume, as in section 2.3.1, that the threshold pressure shift is proportional to some power of the rms pressure of the noise, from two points we can calculate the values of n and C to fit equation (19). The values so calculated are shown in columns (g) and (h) of Table 6. Since measurements of ultimate TTS are liable to errors of at least 1 dB, the margin of error in these calculated values is large - the values of n

Table 7
Relation of ultimate shift to level of noise exposure
(data from Refs 3 and 5)

Source	Noise		Test frequency (Hz)	Shift D' (dB)	Slope	Calculation from equation (19)	
	cf (Hz)	Level (dB)				n	C
(a)	(b)	(c)	(d)	(e)	(f)	(g)	(h)
(1) Ref 3	500	81.5 92.5	750	10 28	1.64	1.90	78.0
(2) Ref 5	500	90 95	707	21 30	1.80	1.91	79.4
(3) Ref 5	2000	80 85	2828	9 14	1.00	1.35	78.2

in cases (1) and (2), for instance, are not reliably different from 2. In case (3), since the shifts are so small, even larger errors are probable. If we had 10 instead of nine in column (e), n would be 1.07; and if we had 8, n would be 1.69. Thus in case (3) one is not really justified in saying more than that the exponent appears to be between 1 and 2. But in cases (1) and (2) one can say with fair confidence that the exponent is about 2.

3.4.2 Averaged results

Mills *et al*⁸ considered averaged results from many sources on the asymptotic threshold shift at the frequency of greatest shift due to exposure to an octave band of noise centred at 4 kHz, and gave empirical formulae to fit the data. Using the symbols used hitherto in this paper, these were:

$$D' = 1.7(L - C) \quad \text{for } 8 < D' < 30 \quad (25)$$

and for a better fit at low levels of TTS

$$D' = 17 \log\{1 + \text{antilog}[(L - C)/10]\} \quad (26)$$

where $C = 74$.

The illustration given in Ref 8, containing averaged data points from many sources is reproduced in Fig 15a. (The curve purporting to represent equation (26) in Ref 8 is shown by the full line, but its correct presentation is as shown by the dotted line.)

Fig 15b shows the same data points, and the curve given by equation (19) for $n = 2$ and $C = 76$, i.e.

$$D' = 20 \log\{1 + \text{antilog}[(L - C)/10]\} . \quad (27)$$

It will be seen that the fit is somewhat better than for the curves in Fig 15a. The line $D' = 2(L - 76)$ is also plotted in Fig 15b, and it will be seen that the apparent exponent is less than 2 for shifts of less than 30 dB. Thus, a straight-line approximation to a pressure square law shift will always yield an apparent exponent less than 2 unless the shifts are large. Also in Ref 8, data from various sources on cats and chinchillas exposed to octave bands of noise are combined in a single plot with data on man, and shown to fit equations (25) and (26) when referenced to values of C varying according to the animal and the frequency of the noise. (Once again the curve is plotted incorrectly in the original paper.) The data points are reproduced in Fig 15c, and the curve shown is given by equation (27), assuming a 2 dB increase in the reference level C . It will be seen that the fit is very good indeed.

Thus, it is clear that the figures for asymptotic threshold shift quoted by Mills *et al* can be fitted by a simple pressure squared law - a much more manageable, and perhaps theoretically explicable, form than that proposed by Mills.

Part of the reason why many experimenters try to fit straight lines to shift/exposure-level data is that they wish to fix on critical levels below which no serious danger to hearing is incurred, and the intersection of straight lines gives a very clear fix. The critical level is taken to be that at which equation (25) meets the zero shift line, that is, C dB is taken to be the critical level. But it is clear that the value of C will vary according to the range of threshold shifts involved: the smaller the shifts the flatter the curve and the lower the value of C . It would be more consistent to fix on an arbitrary level of mean shift, and regard the level of noise giving rise to that shift as the critical level - though, indeed, it has yet to be shown conclusively that TTS has any bearing on permanent threshold shift.

3.5 Comparison with published data on TTS due to intermittent exposure to noise

It may be said at once that published data do not agree well with the analysis presented in section 2.2. No results for individuals have been found, but averaged results for the levels reached after certain exposures are given in Ref 9, and in Ref 10 which also reports recovery.

Ward *et al*⁹ exposed subjects for 2 hours to 45-second bursts of octave bands of noise of various frequencies, alternating with 45-second bursts of weaker noise of the same kind, in the first tests so weak as to be effectively quiet. In each test TTS_2 and TTS_{120} for the two ears of each of five subjects at 2.8, 4 and 5.6 kHz were measured and averaged. The level of the louder noise was maintained constant, and the level of the weaker noise was increased in subsequent tests, up to about 10 dB below the level of the louder noise. From a plot of the threshold against the level of the weaker noise, the level L dB, of this noise was determined for which the shift began to increase above the shift, D_H dB for the louder noise, H dB, alternating with quiet. L was called the critical level. The results for TTS_2 are summarized in columns (a) to (d) of Table 8 below.

Table 8

Determination of critical levels (data from Ref 9)

Noise cf (kHz)	Noise levels (dB)		Threshold shifts (dB)			Calculate L' (dB)	
	H(igh)	L(ow)	D_H	D'_H	D'_L	$n = 2$	$n = 1$
(a)	(b)	(c)	(d)	(e)	(f)	(g)	(h)
0.25	105	77	6.0	16.9	7.9	98.9	92.8
0.5	100	76	6.5	17.8	8.2	93.7	87.3
1	95	69*	5.5	16.1	7.6	89.2	83.3
2	90	68	7.5	19.4	8.8	83.2	76.5
4	90	60*	17.0	31.6	15.9	81.5	73.0

* Said to be doubtful because of "lack of monotonicity of the data."

Columns (e) to (h) give various figures derived from the data and from Appendix C, assuming a time constant of 300 minutes throughout. Details of the calculations are given at the end of Appendix C.

Column (e) gives the ultimate shift, D'_H dB, to be expected according to equation (C-11) for continuous exposure to H dB. Column (f) gives the ultimate shift, D'_L dB, for a continuous exposure to a level L' dB where H and L' alternating would increase D'_H by 1 dB. Columns (g) and (h) give the values of L' according to a square or linear pressure law (equation (20)) which would produce the shifts of column (f).

The constants used in these calculations are almost arbitrary, so one would not expect exact agreement with experimental results. Nevertheless, the figures in columns (g) and (h) show the order of the level of weaker noise which would be expected (according to the analysis of Appendix C) to produce the

observed effects, following either the square or the linear pressure law. The differences between the values of L and L' are so large, of the order of 20 dB for the square law and 12 dB for the linear law, that it is clear some other explanation is required.

Another fairly recent paper by Hétu and Tremolières¹⁰ describes an experiment in which 20 subjects were exposed to equal periods of broad-band noise of alternately lower and higher levels. The total period of exposure in each case was 128 minutes, and the cycles (one exposure at low level followed by one at high level) lasted 1, 8, 32 or 64 minutes. The levels used were:

- (1) effective quiet alternating with noise at 99 dB(A)
- (2) noise at 93 dB(A) alternating with noise at 98 dB(A).

In addition there was a continuous exposure to noise at 96 dB(A). Averaged threshold shifts for all ears at 4 and 6 kHz at 7 minutes and at subsequent times up to 4 hours after the end of the exposure are reported. All the results show more or less linear recovery against a log-time scale, and nearly complete recovery at 4 hours.

The results for the second type of alternating noise show a variation of TTS_7 from about 19 dB for the shortest cycle to just over 20 dB for the longest, compared with 21.5 for the continuous noise. These differences are said not to be statistically significant, and can be shown not to be inconsistent with the analysis of Appendix C. But for the first series of tests, the results are approximately as follows:

Cycle time (minutes)	1	8	32	64
TTS_7 (dB)	11.5	15.5	17	19.5

but equations (C-16) and (C-17) show that if the exponential pressure law holds, the difference between the ultimate levels reached for very long cycles and for infinitesimal cycles cannot exceed 6 dB. Obviously, we have less variation than this in cycle length here, and the ultimate levels have probably not been attained, and both these factors should tend to reduce the range between the shifts for the shortest and longest cycles. But the difference is actually 8 dB. It is clear therefore that these results are not compatible with the simple exponential pressure theory.

3.6 Variation of recovery patterns from the same level

It has been found by some experimenters that the form of the recovery from a given TTS at a given frequency is not independent of the characteristics of the noise which produced the shift. (Burns² discusses this problem on p 207.)

The fact that in this Memorandum, it has often been necessary to postulate a double exponential to represent growth and, more particularly, recovery curves for individuals suggests an explanation. It has already been pointed out (section 3.3.1) that if mechanisms having different time constants are present in one ear, growth tends to be dominated by the shorter time constant and recovery by the longer one. Now, suppose we have two such mechanisms, with time constants T_1 and T_2 where $T_1 > T_2$, and we have a shift to, say D dB, after exposure to two different noises, N and N' . Now suppose N has produced the shift D with the time constant T_1 , while at the same time producing a shift E dB, where $E < D$, with the time constant T_2 . Then in recovery the longer time constant T_1 will operate throughout. On the other hand, suppose N' has produced the shift D with time constant T_2 , and at the same time a shift to E' , where $E' < D$, with the time constant T_1 . Here in recovery the shorter time constant will operate until a level rather less than E' is reached, when the longer time constant will take over. Of course, if E' were very small, the effect of the longer time constant might not appear at all. There is no reason, of course, why the number of mechanisms involved should be limited to two; the argument has been restricted to two mechanisms for the sake of simplicity. Thus, wide variations of recovery patterns from the same shift are possible, composed to different extents by systems with different time constants.

3.7 Summary of comparisons with published data

Comparisons with published data have shown that in general the growth of individual threshold shifts fits well with the pressure exponential law, though sometimes two systems are required. For averaged results also, as represented by the accepted straight-line forms, the fit is good over limited ranges.

Agreement with recovery forms for individuals is not quite so good as for growth and frequently requires the postulation of at least two systems to obtain a good fit. Often also the last stages of recovery appear to be governed by very long time constants. The analysis has shown that longer time constants, if they exist in the same ear with shorter ones, may not be observed during growth but will dominate recovery. An enormous range of individual responses exist - for one condition (see Table 3) the range of time constants in 12 ears was from 5 to 1200 minutes, and the range of shifts from 5 to 37 dB.

It has been shown that the average ultimate shifts for tests at particular frequencies after exposure to particular types of noise can be represented by

the simple formula for the response to a pressure square⁴ law:

$$D' = 20 \log\{1 + \text{antilog}[(L - C)/10]\} \quad (28)$$

where L dB is the noise level and C is a constant for the particular circumstances. C appears to be about 2 dB greater than the 'critical level' proposed by, *eg* Mills⁸.

Attempts to match the exponential pressure law to some published results on intermittent exposure were unsuccessful, possibly due to the fact that comparisons with averaged data only were made, but possibly to more fundamental causes.

The possibility that more than one mechanism may be involved in producing TTS suggests reasons why recovery from the same level of TTS at a given frequency may vary according to the type of noise which produced it.

4 CONCLUSION

Analysis of the forms to be expected if temporary threshold shift were governed by simple exponential pressure rules have been presented, and the results have been compared with a limited selection of published data. It has been shown that the rules adequately represent conditions during the growth of TTS in steady noise, and slightly less well the conditions during recovery, at least for individual ears. It has also been shown that the ultimate or asymptotic threshold shift for given types of noise and test frequencies, can be simply expressed if the shift of threshold pressure is assumed proportional to the square of the noise pressure. These simple rules do not appear to fit data on intermittent exposures, and here further investigation is required.

As a general conclusion, it is believed that much of the difficulty in understanding TTS can be ascribed to three main causes:

- (1) The difficulties inherent in threshold measurements make for inexact data.
- (2) The habit of averaging widely scattered results prevents the understanding of the mechanisms involved.
- (3) The automatic use of the dB and the custom of trying to fit straight lines to every set of results have prevented the recognition of many simple effects. It is hoped that the analytic curves given in this paper may help experimenters to recognize the underlying principles even though results are presented in dB.

Only a very limited selection of data has been studied; a much more comprehensive survey would be necessary before the conclusions reached here could be applied with confidence to all circumstances. Intermittent exposures, in particular, require further study. Also many facets of TTS (such as its relation to permanent threshold shift) have not been considered here at all. Even so, it is believed that the procedures given here point the way to better understanding of TTS, and possibly of other acoustic phenomena.

Appendix A

TANGENT AT ORIGIN OF dB/lin-TIME PLOT

We start from equation (2) of section 2.1.1 (using the same symbols)

$$D = 20 \log\{1 + [1 - \exp(-t/T)] [\text{antilog}(D'/20) - 1]\} \quad (A-1)$$

For convenience, write $[\text{antilog}(D'/20) - 1] = A$, and $t/T = x$ and we may then write

$$D = 20 \log e \ln\{1 + A[1 - e^{-x}]\} \quad (A-2)$$

$$dD/dx = 20 \log e A e^{-x} / \{1 + A[1 - e^{-x}]\} \quad (A-3)$$

if $n = 0$,

$$dD/dx = 20A \log e \quad .$$

Hence the tangent at $x = 0$ is

$$D = 20 Ax \log e \quad (A-4)$$

which meets $D = D'$

$$\text{where} \quad x = T'/T = D' / \{20 \log e [\text{antilog}(D'/20) - 1]\} \quad (A-5)$$

Appendix B

TANGENT OF INFLEXION ON dB/log-TIME PLOT

We start from equation (2) of section 2.1.1

$$D = 20 \log \{1 + [1 - \exp(-t/T)] [\text{antilog}(D'/20) - 1]\} . \quad (\text{B-1})$$

As in Appendix A, let $t/T = x$ and $\text{antilog}(D'/20) - 1 = A$. Also since we are concerned with the slope relative to the log of (t/T) , let $\log x = y$.

Then

$$dx/dy = x/(\log e) = x \ln 10 \quad (\text{B-2})$$

$$D = 20 \log e \ln \{1 + A[1 - e^{-x}]\} .$$

Hence

$$dD/dy = (dD/dx)(dx/dy) = 20Ax e^{-x} / \{1 + A[1 - e^{-x}]\} \quad (\text{B-3})$$

$$\frac{d^2D}{dy^2} = \frac{d}{dx} \left(\frac{dD}{dy} \right) \frac{dx}{dy} = \frac{20Ax e^{-x} \{1 - x + A[1 - x - e^{-x}]\}}{\log e \{1 + A[1 - e^{-x}]\}^2} \quad (\text{B-4})$$

$$d^2D/dy^2 = 0 \text{ when } x = x_1 ,$$

$$\text{where } 1 - x_1 + A[1 - x_1 - e^{-x_1}] = 0 , \quad (\text{B-5})$$

the other possible solutions being trivial.

It is convenient to express all the variables in terms of x_1

$$\left. \begin{aligned} A &= (x_1 - 1) / [1 - x_1 - e^{-x_1}] \\ D' &= 20 \log(A + 1) = -20 \log [1 + (x_1 - 1)e^{x_1}] \end{aligned} \right\} \cdot (\text{B-6})$$

The slope at $y = \log x_1$ is $20(1 - x_1)$
and the value of D is

$$D_1 = 20 \log \left\{ x_1 / [1 + (x_1 - 1)e^{x_1}] \right\} = 20 \log x_1 + D'$$

Hence the tangent at the point of inflexion is

$$D = 20 \log \left\{ x_1 / \left[1 + (x_1 - 1)e^{x_1} \right] \right\} + 20(1 - x_1) \log(x/x_1) \quad (\text{B-7})$$

which meets $D = D'$ where $t = T'$, say, and $T'/T = x_1^z$

where
$$z = x_1 / (x_1 - 1) \quad . \quad (\text{B-8})$$

This gives the time of the intercept of (B-7) on $D = D'$ from the beginning of growth or decay. Alternatively, the difference between the times for $D = D'$ and $D = 0$ might be used. This would give $t = T'' = T' - T_0$, say where

$$T_0/T = T' \left[1 + (x_1 - 1)e^{x_1} \right]^{1-z}$$

Hence

$$T''/T = T' \left\{ 1 - \left[1 + (x_1 - 1)e^{x_1} \right]^{1-z} \right\} \quad (\text{B-9})$$

Appendix C

ALTERNATING EXPOSURES TO TWO DIFFERENT NOISE LEVELS

Using the symbols of section 2.2, we can apply equation (1) to each sub-exposure separately and hence obtain the equations

$$x_{2n-1} = x_{2n-2} + (P_2 - x_{2n-2}) [1 - \exp(-t_1/T)] = p_2(1 - y) + yx_{2n-2} \quad (C-1)$$

and

$$x_{2n} = x_{2n-1} + (P_2' - x_{2n-1}) [1 - \exp(-qt_1/T)] = p_2'(1 - y^q) + y^q x_{2n-1} \quad \dots\dots(C-2)$$

We may substitute in C_2 from C_1 , thus eliminating the odd-numbered terms

$$\begin{aligned} x_{2n} &= p_2'(1 - y^q) + y^q [p_2(1 - y) + yx_{2n-2}] \\ &= y^{q+1}x_{2n-2} + p_2y^q(1 - y) + p_2'(1 - y^q) \end{aligned}$$

and similarly

$$\begin{aligned} x_{2n-2} &= y^{q+1}x_{2n-4} + p_2y^q(1 - y) + p_2'(1 - y^q) \\ &\quad | \quad | \quad | \quad | \\ &\quad | \quad | \quad | \quad | \\ x_4 &= y^{q+1}x_2 + p_2y^q(1 - y) + p_2'(1 - y^q) \\ x_2 &= y^{q+1}x_0 + p_2y^q(1 - y) + p_2'(1 - y^q) \\ x_0 &= p_1 \end{aligned} \quad \left. \vphantom{\begin{aligned} x_{2n-2} \\ x_4 \\ x_2 \\ x_0 \end{aligned}} \right\} \quad (C-3)$$

Similarly for the odd-numbered terms, we find

$$\begin{aligned} x_{2n-1} &= y^{q+1}x_{2n-3} + p_2(1 - y) + p_2'y(1 - y^q) \\ x_{2n-3} &= y^{q+1}x_{2n-5} + p_2(1 - y) + p_2'y(1 - y^q) \\ &\quad | \quad | \quad | \\ &\quad | \quad | \quad | \\ x_3 &= y^{q+1}x_1 + p_2(1 - y) + p_2'y(1 - y^q) \\ x_1 &= yp_1 + p_2(1 - y) \end{aligned} \quad \left. \vphantom{\begin{aligned} x_{2n-1} \\ x_{2n-3} \\ x_3 \\ x_1 \end{aligned}} \right\} \quad (C-4)$$

Then multiplying successive equations of C_3 by, $1, y^{q+1}, y^{2(q+1)}, \dots, y^{(q+1)}$, and adding, we have

$$\begin{aligned} x_{2n} &= p_1 y^{n(q+1)} + \left[p_2 (1-y)y^q + p_2' (1-y^q) \right] [1 + y^{q+1} + \dots + y^{(n-1)(q+1)}] \\ &= p_1 y^{n(q+1)} + \left[p_2 (1-y)y^q + p_2' (1-y^q) \right] [1 - y^{n(q+1)}] / [1 - y^{(q+1)}] . \\ &\dots\dots (C-5) \end{aligned}$$

Similarly from (C-4)

$$\begin{aligned} x_{2n-1} &= p_1 y^{(n-1)(q+1)+1} + \left[p_2 (1-y)(1 - y^{n(q+1)}) \right. \\ &\quad \left. + p_2' y(1 - y^q)(1 - y^{(q+1)(n-1)}) \right] / [1 - y^{(q+1)}] . \quad (C-6) \end{aligned}$$

Special cases

(1) If first noise is effectively silence, i.e. $p_2 = p_1$

$$x_{2n} = \left\{ p_1 [y^{n(q+1)}(1 - y^q) + p^q(1 - y)] + p_2'(1 - y^q)(1 - y^{n(q+1)}) \right\} / [1 - y^{(q+1)}] \dots\dots (C-7)$$

$$x_{2n-1} = \left\{ p_1 [(1 - y) + y^{n(q+1)-q}(1 - y^q)] + p_2' y(1 - y^q)(1 - y^{n(q+1)}) \right\} / [1 - y^{(q+1)}] \dots\dots (C-8)$$

(2) If exposure times are equal, i.e. $q = 1$ (the most common experimental case).

$$x_{2n} = p_1 y^{2n} + \left[p_2 y + p_2' \right] (1 - y^{2n}) / (1 + y) \quad (C-9)$$

$$x_{2n-1} = p_1 y^{2n-1} + \left[p_2 (1 - y^{2n}) + p_2' y(1 - y^{2(n-1)}) \right] / (1 + y) . \quad (C-10)$$

(3) $p_2 = p_1$ and $q = 1$.

$$x_{2n} = \left[p_1 (y + y^{2n}) + p_2' (1 - y^{2n}) \right] / (1 + y) \quad (C-11)$$

$$x_{2n-1} = \left[p_1 (1 + y^{2n-1}) + p_2' (1 - y)(1 - y^{2(n-1)}) \right] / (1 + y) . \quad (C-12)$$

Ultimate pressure threshold shifts

Since $y = \exp(-t_1/T)$ is necessarily less than unity, $y^{2n} \rightarrow 0$ as $n \rightarrow \infty$. Hence, in the general expressions (equations (C-5) and (C-6)),

$$x_{2n} \rightarrow \left[p_2 y^q (1 - y) + p_2' (1 - y^q) \right] / \left[1 - y^{(q+1)} \right] \quad (C-13)$$

$$x_{2n-1} \rightarrow \left[p_2 (1 - y) + p_2' y (1 - y^q) \right] / \left[1 - y^{(q+1)} \right] . \quad (C-14)$$

If both t_1 and qt_1 are small compared with T ,

$$y \simeq 1 - t_1/T, \quad y^q \simeq 1 - qt_1/T$$

so that

$$x_{2n-1} \rightarrow x_{2n} \rightarrow (p_2 + qp_2') / (1 + q) . \quad (C-15)$$

In the special case where $q = 1$

$$x_{2n-1} \rightarrow x_{2n} \rightarrow (p_2 + p_2') / 2 . \quad (C-16)$$

If both t_1 and qt_1 are large compared with T , y and y^q are small so that

$$x_{2n} \rightarrow p_2' \quad \text{and} \quad x_{2n-1} \rightarrow p_2 , \quad (C-17)$$

as might be expected

Hence the ratio of the pressure thresholds for very long and very short exposure periods tends to

$$R_{2n} = 2p_2'(q + 1) / (p_2 + qp_2') . \quad (C-18)$$

If $q = 1$

$$R_{2n} = 2p_2' / (p_2 + p_2') , \quad (C-19)$$

which is always less than 2.

Hence the difference between the ultimate shift for continuous exposure and the ultimate shift for very short exposures alternating with equal periods of quiet can never exceed 6 dB.

Analysis for section 3.5, Table 7

Initially we have a noise level H dB alternating with quiet in 45-second bursts producing a shift of D_H dB after 2 hours.

If $T = 300$, $t_1/T = 1/400$. After 2 hours, $2n = 160$, $y = 0.9975$, $y^{2n} = 0.6703$.

Hence, using equation (C-11),

$$(p_2'/p_1) = \left[(1 + y) \text{antilog}(D_H/20) - y - y^{2n} \right] / (1 - y^{2n})$$

$$D_H' = 20 \log(P_2'/P_1) = 20 \log\{6.059 \text{antilog}(D_H/20) - 5.059\} .$$

For a change of 1 dB in shift at 2 hours, we need to introduce into quiet periods a noise which would give a threshold shift of D_L' dB where, from equation (C-9)

$$20 \log \left\{ y^{2n} + \left[y \text{antilog}(D_L'/20) + \text{antilog}(D_H'/20) \right] (1 - y^{2n}) / (1 + y) \right\} = D_H + 1$$

$$\begin{aligned} y \text{antilog}(D_L'/20) (1 - y^{2n}) / (1 + y) &= \text{antilog} \left[(D_H + 1)/20 \right] - y^{2n} \\ &\quad - \left[\text{antilog}(D_H/20) - (y + y^{2n}) / (1 + y) \right] \\ &= \text{antilog}(D_H/20) \left[\text{antilog}(1/20) - 1 \right] \\ &\quad + y(1 - y^{2n}) / (1 + y) . \end{aligned}$$

Therefore

$$\begin{aligned} D_L' &= 20 \log \left\{ \text{antilog}(D_H/20) [\text{antilog}(1/20) - 1] y(1 + y) / (1 - y^{2n}) + 1 \right\} \\ &= 20 \log\{0.7374 \text{antilog}(D_H/20) + 1\} . \end{aligned}$$

If a power law applies (equation (19))

$$D_H' = 20 \log\{1 + \text{antilog}[n(H - C)/20]\}$$

$$D_L' = 20 \log\{1 + \text{antilog}[n(L - C)/20]\}$$

$$L = H - (20/n) \log \left\{ [\text{antilog}(D_H'/20) - 1] / [\text{antilog}(D_L'/20) - 1] \right\} .$$

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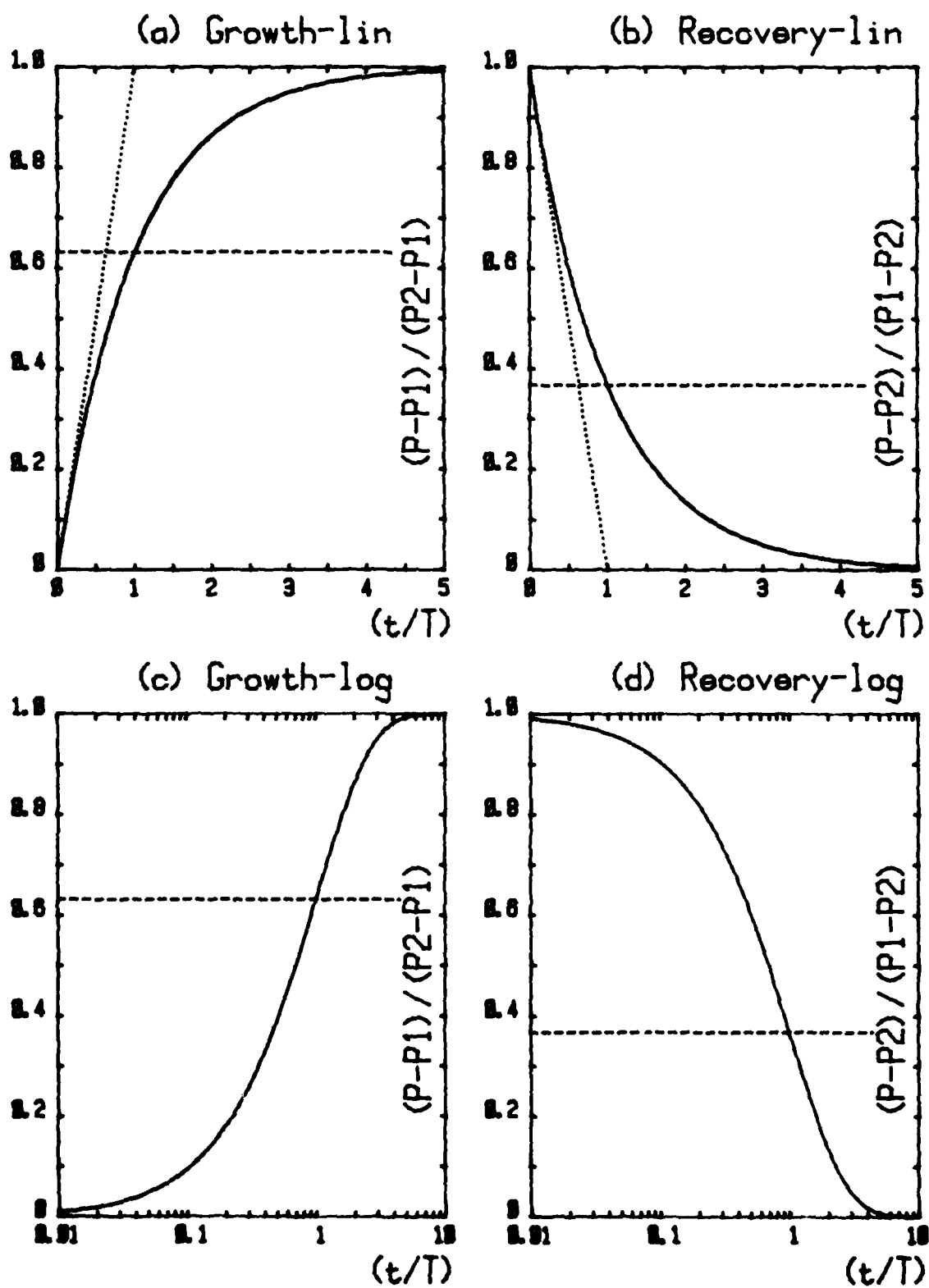


Fig 1a-d Exponential pressure growth and recovery (pressure ratio v time ratio)

Fig 2a-d

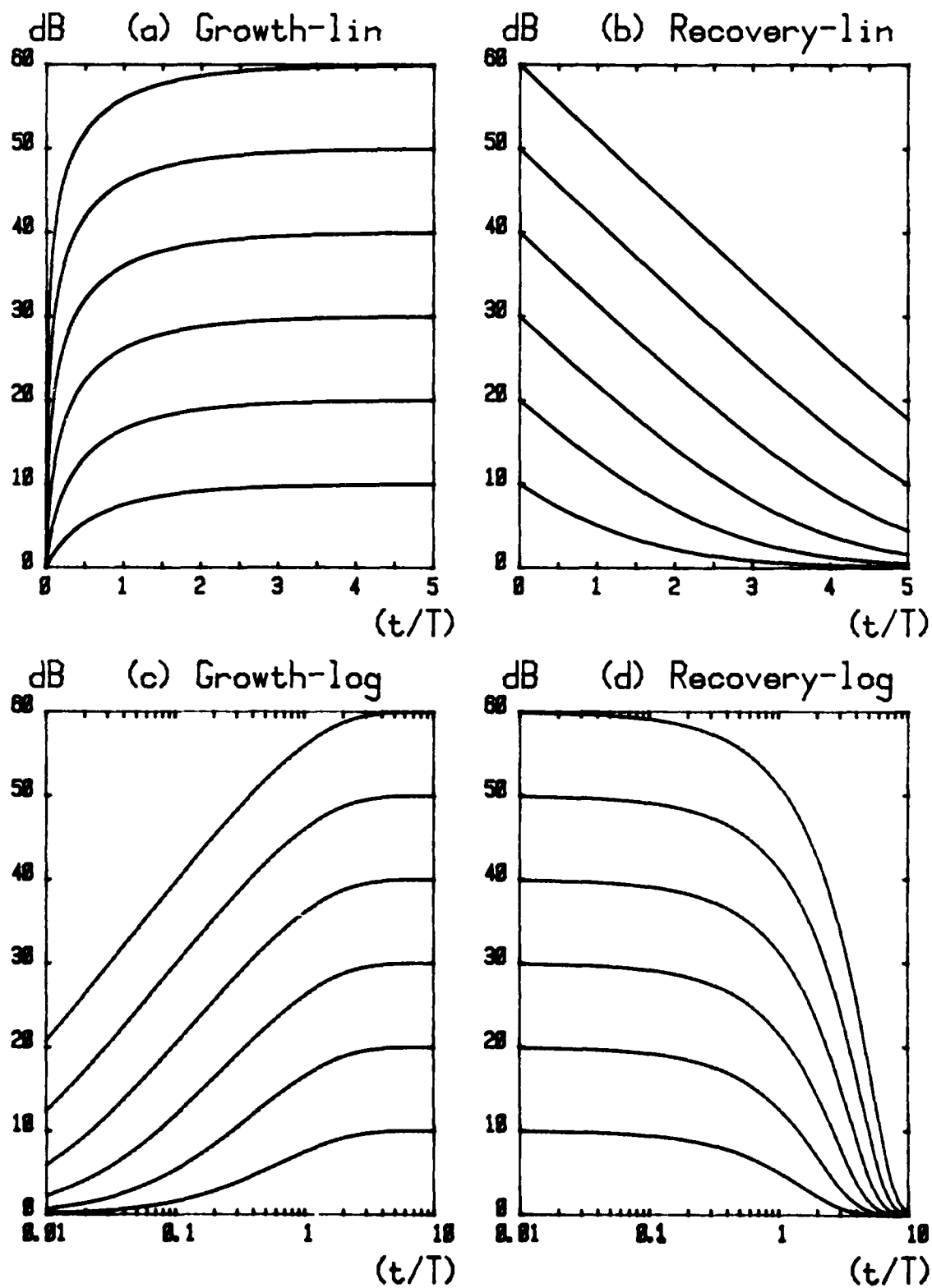


Fig 2a-d Exponential pressure growth and recovery (dB v time ratio)

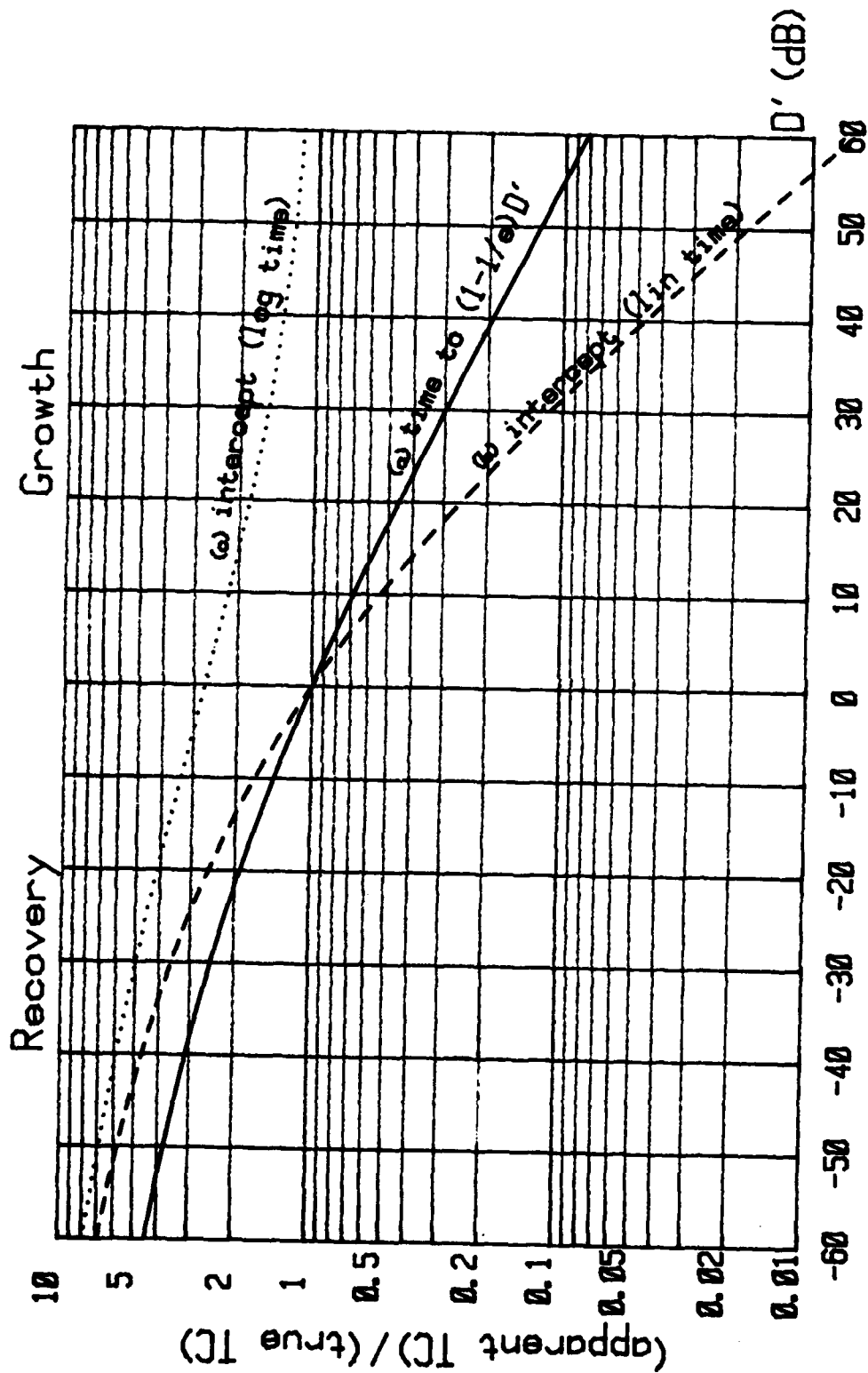


Fig 3 Time constant derived from dB v time plots

Fig 4

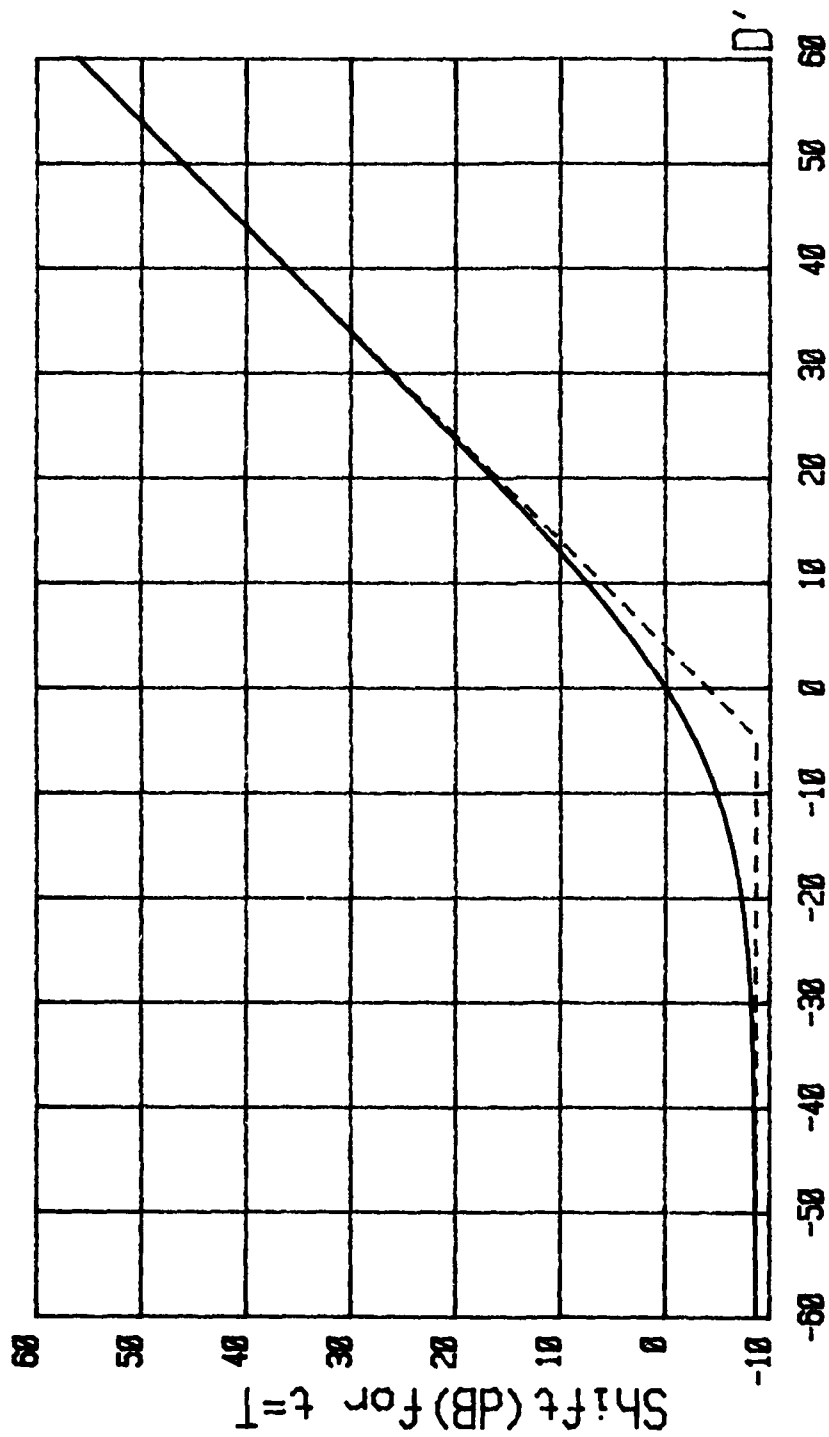


Fig 4 Variation of shift for $t = T$ with ultimate shift

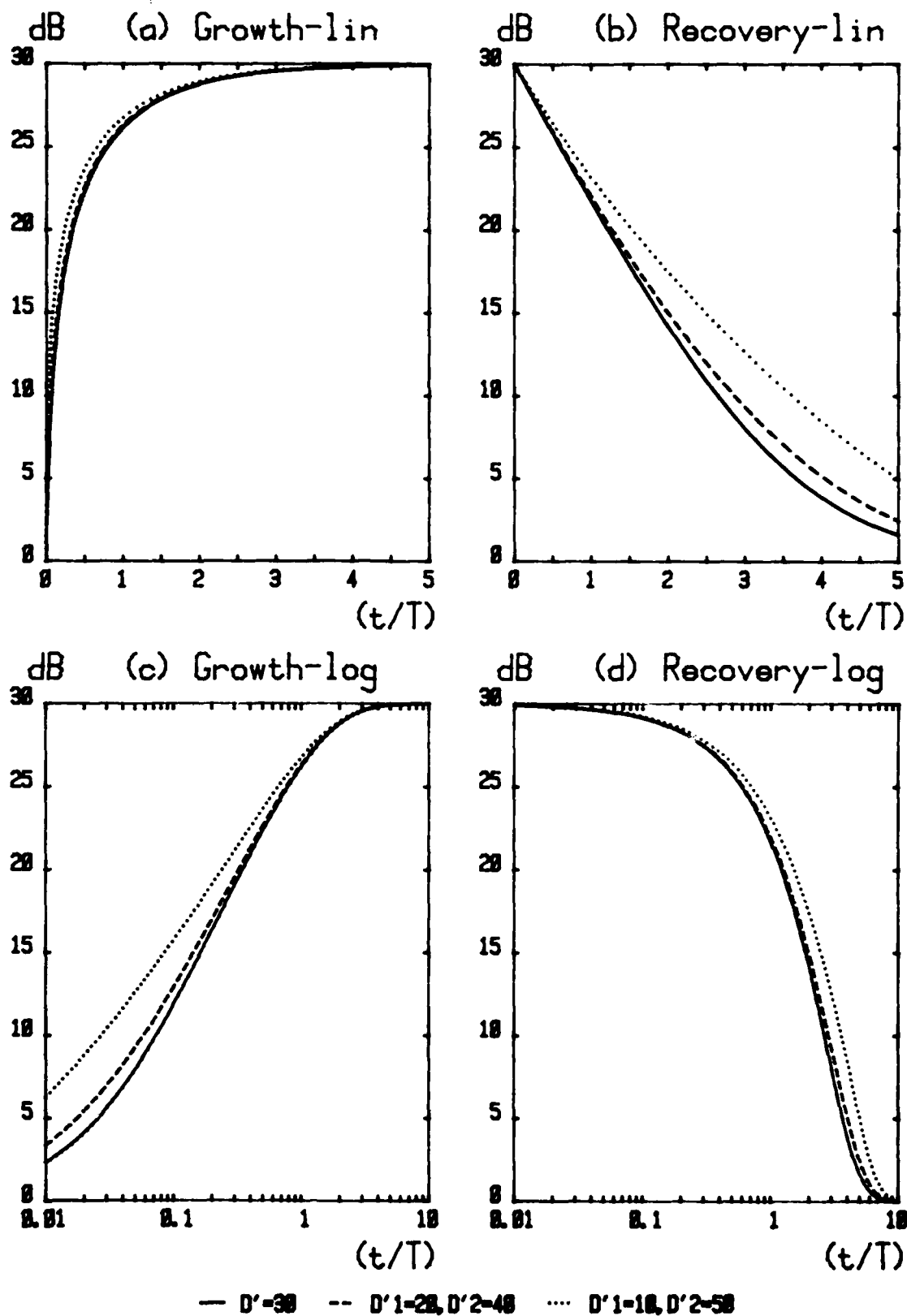
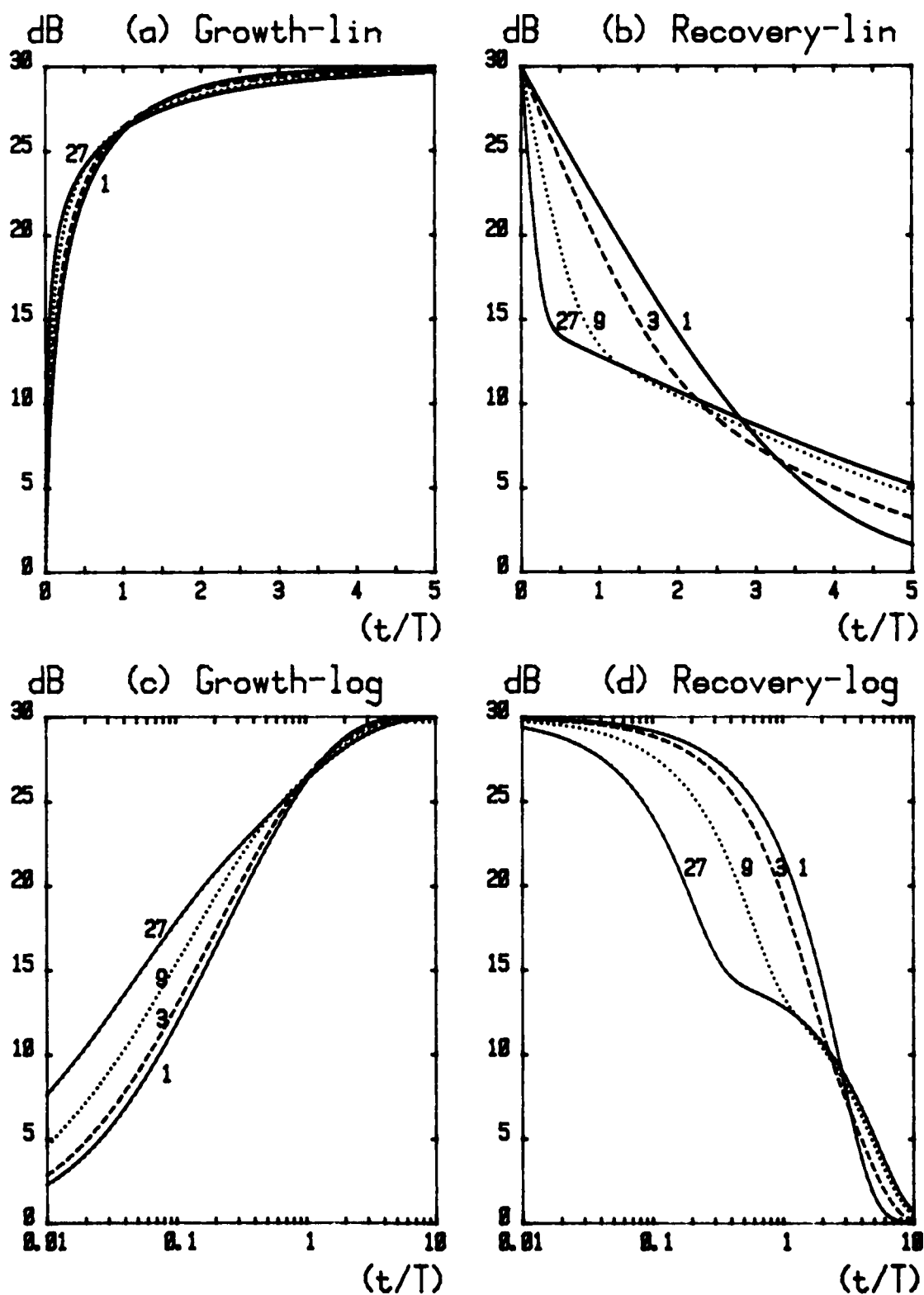


Fig 5a-d Average growth and recovery for shifts to (1) 20 and 40 dB and (2) 10 and 50 dB compared with shift to 30 dB (same time constants)

Fig 6a-d



The parameter is (T_1/T_2) , $T = (T_1 + T_2)/2$

Fig 6a-d Average growth and recovery of shifts to 30 dB with time constants T_1 and T_2

Fig 7

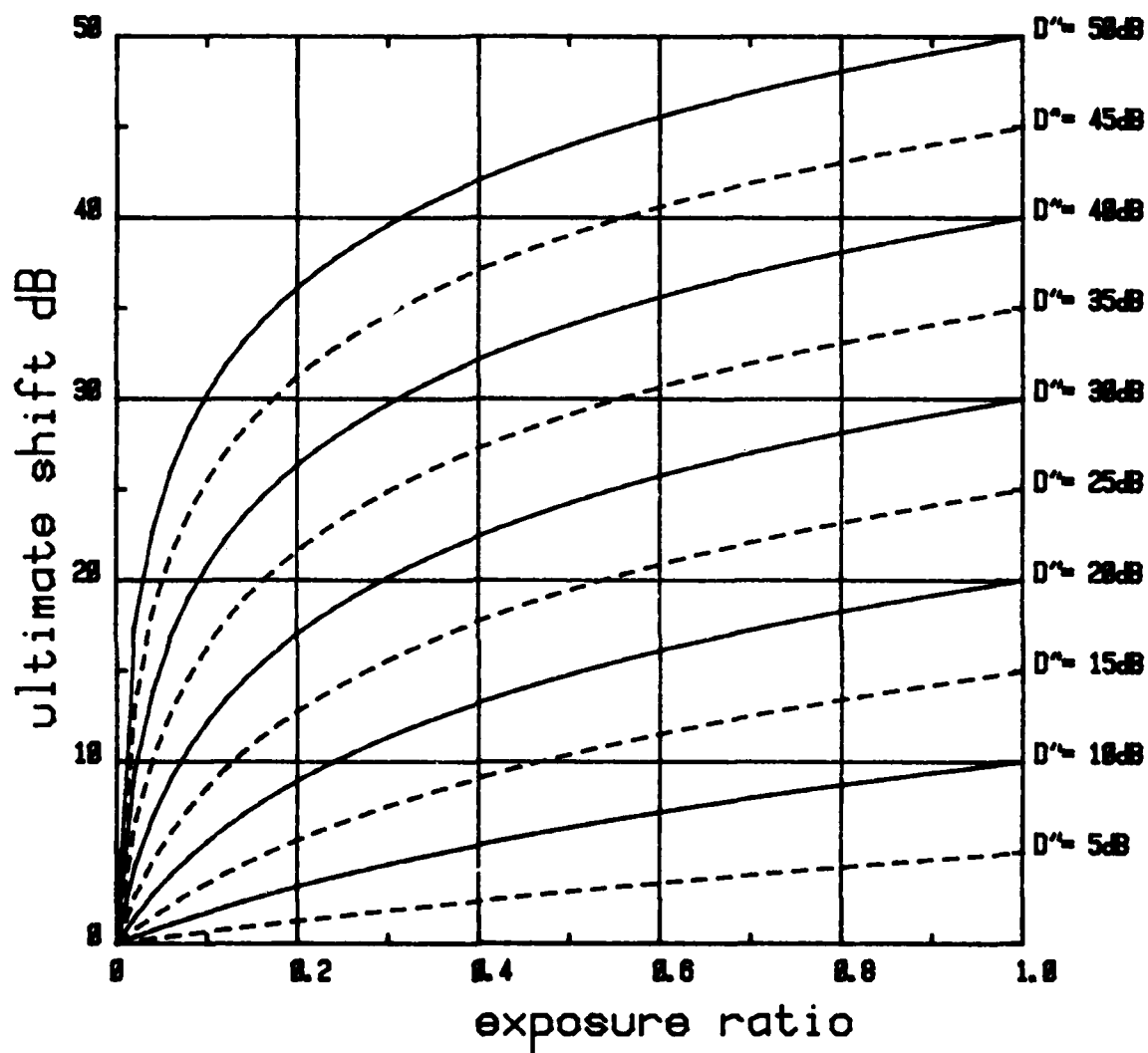
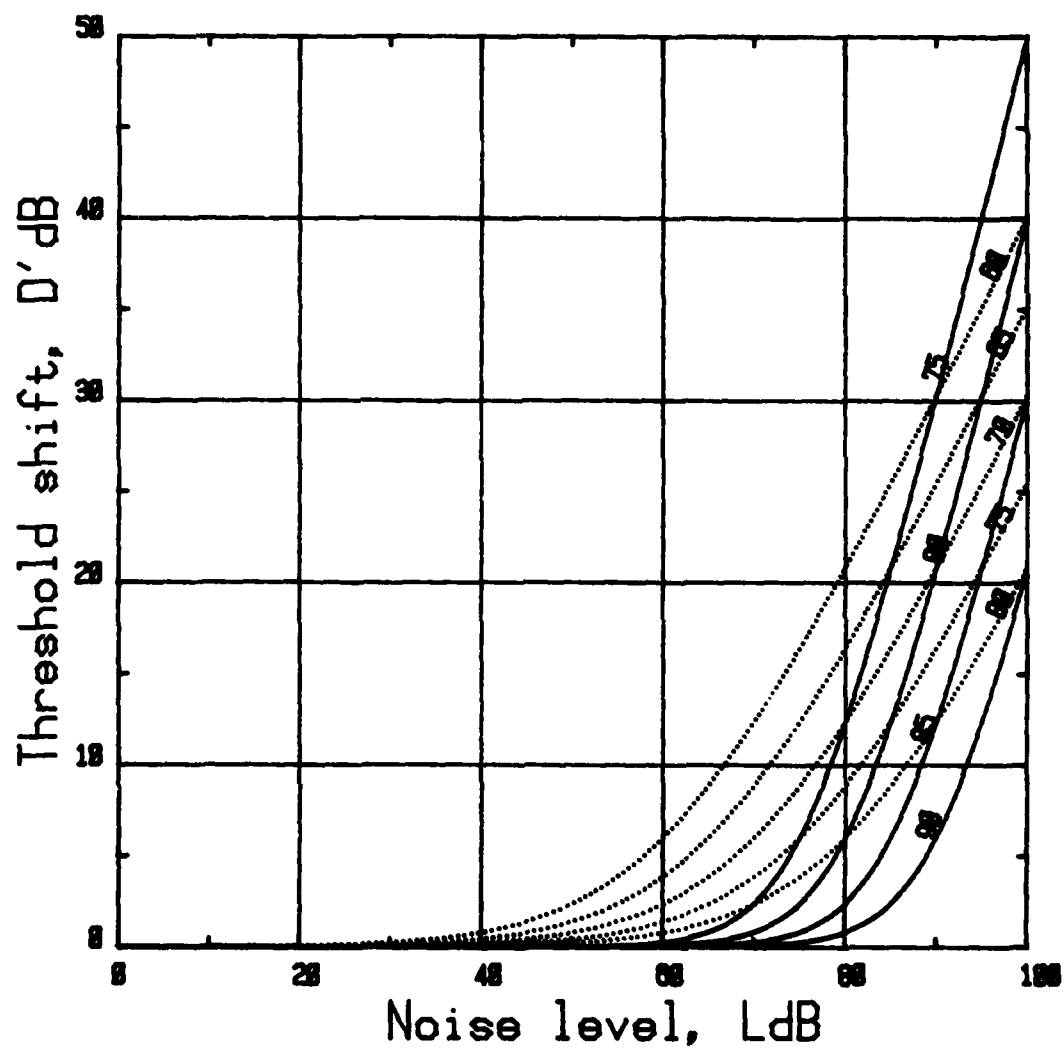


Fig 7 Variation of ultimate shift with exposure ratio for short repetitive exposures to noise

Fig 8

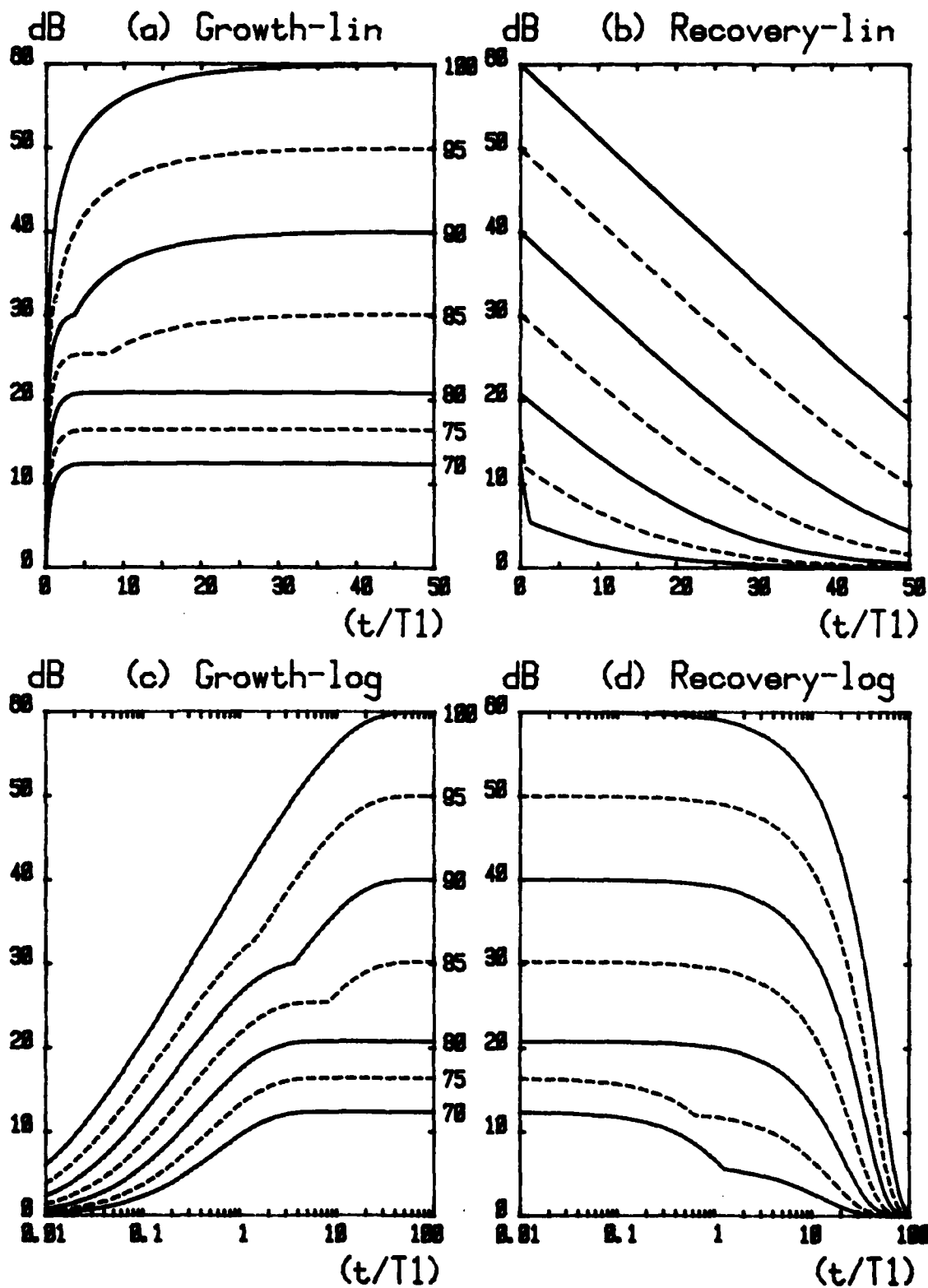


..... $D' = 20 \log(1 + \text{antilog}[(L - C)/20])$

———— $D' = 20 \log(1 + \text{antilog}[(L - C)/10])$

The parameter is C dB

Fig 8 Ultimate shifts according to linear and square law



The parameter is the noise level in dB

Fig 9a-d Growth and recovery governed by double exponential pressure law (see section 2.3.2 for constants)

Fig 10a&b

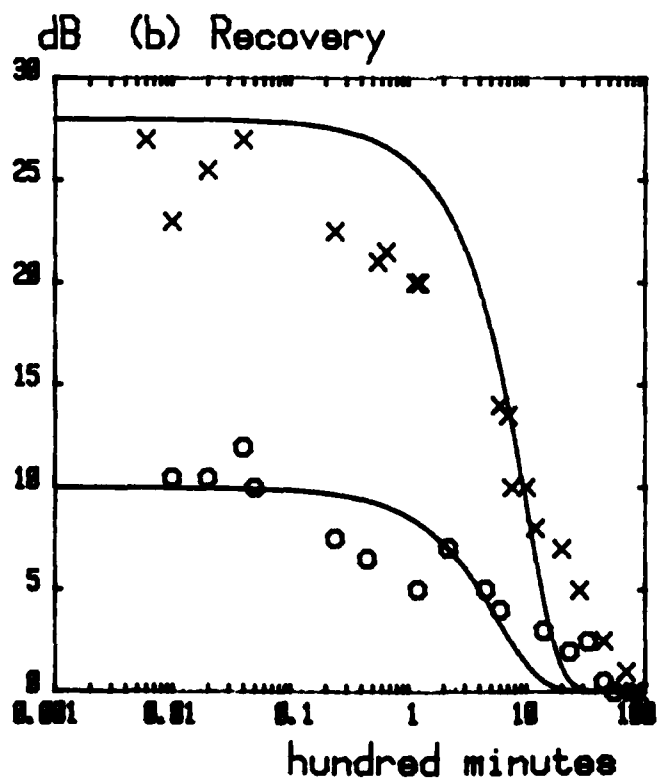
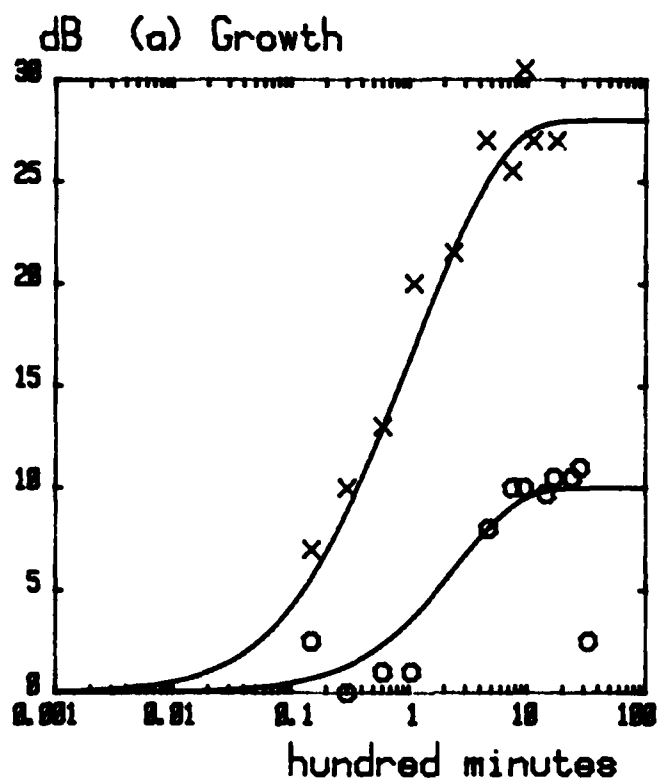


Fig 10a&b Comparison of data for an individual (after Mills *et al*, Ref 3) with theory

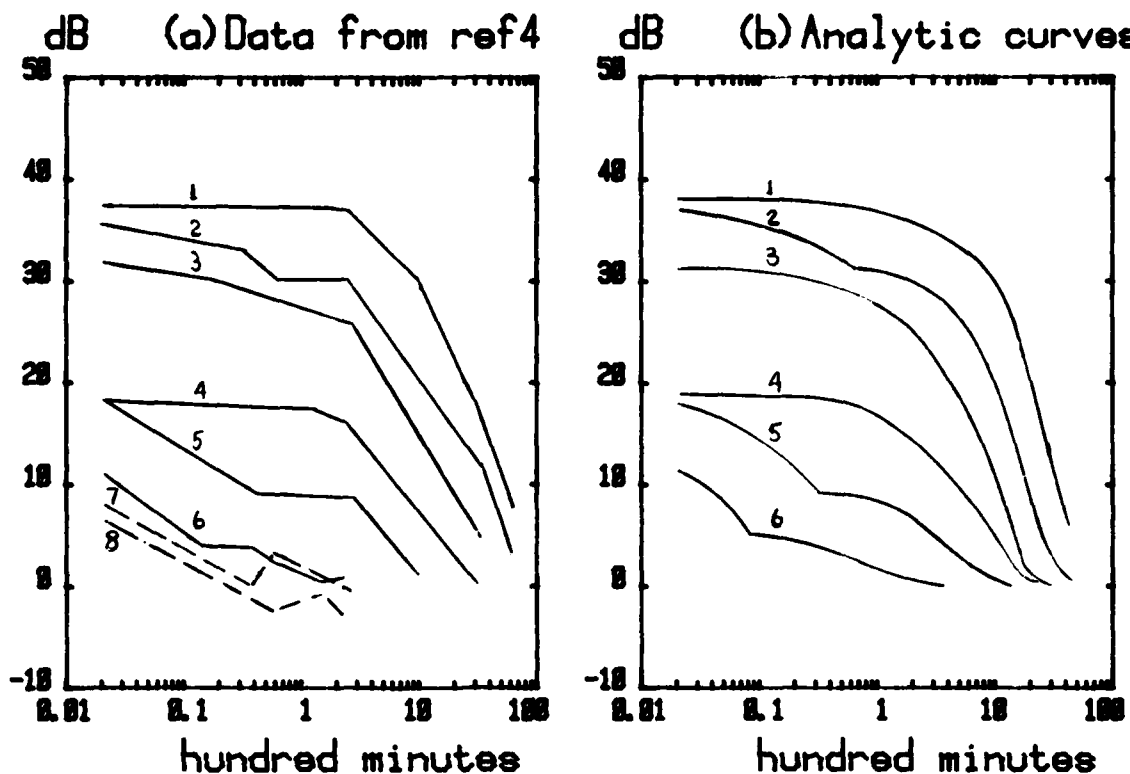


Fig 11a&b Comparison with data for individual ears (after Ward, Ref 4)
(see Table 3)

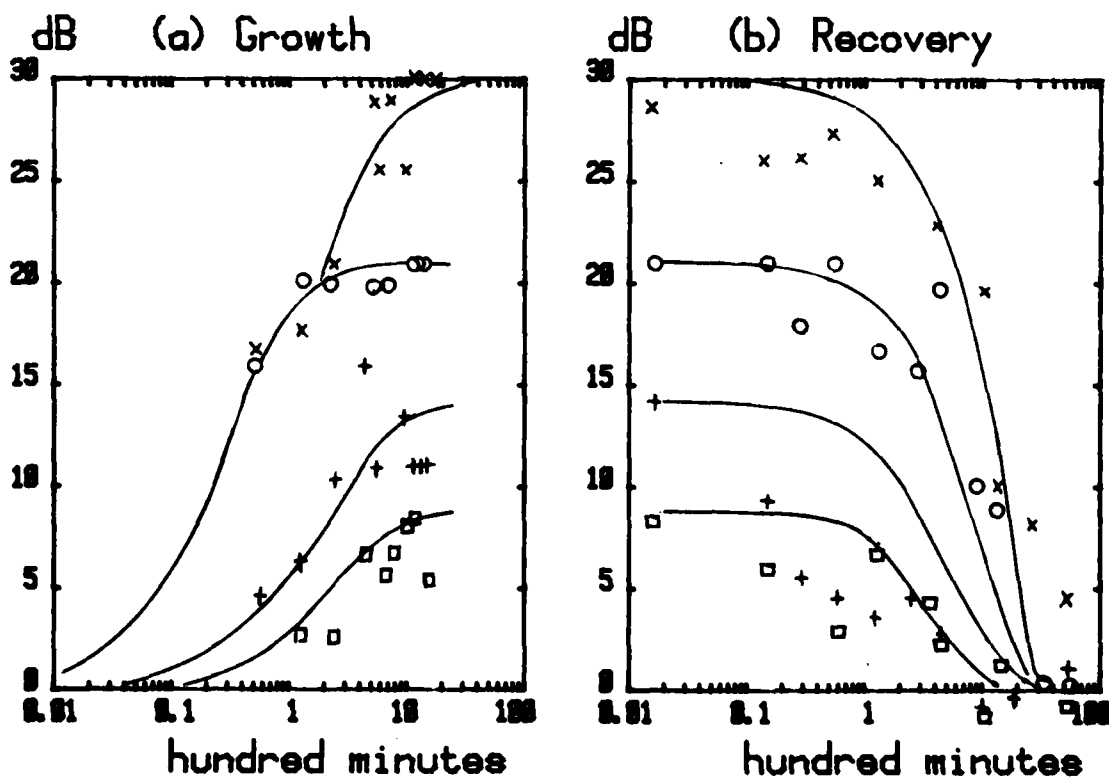


Fig 12a&b Comparison of data for an individual (after Barry, Ref 5,
see Table 4) with theory

Figs 13a&b and 14a&b

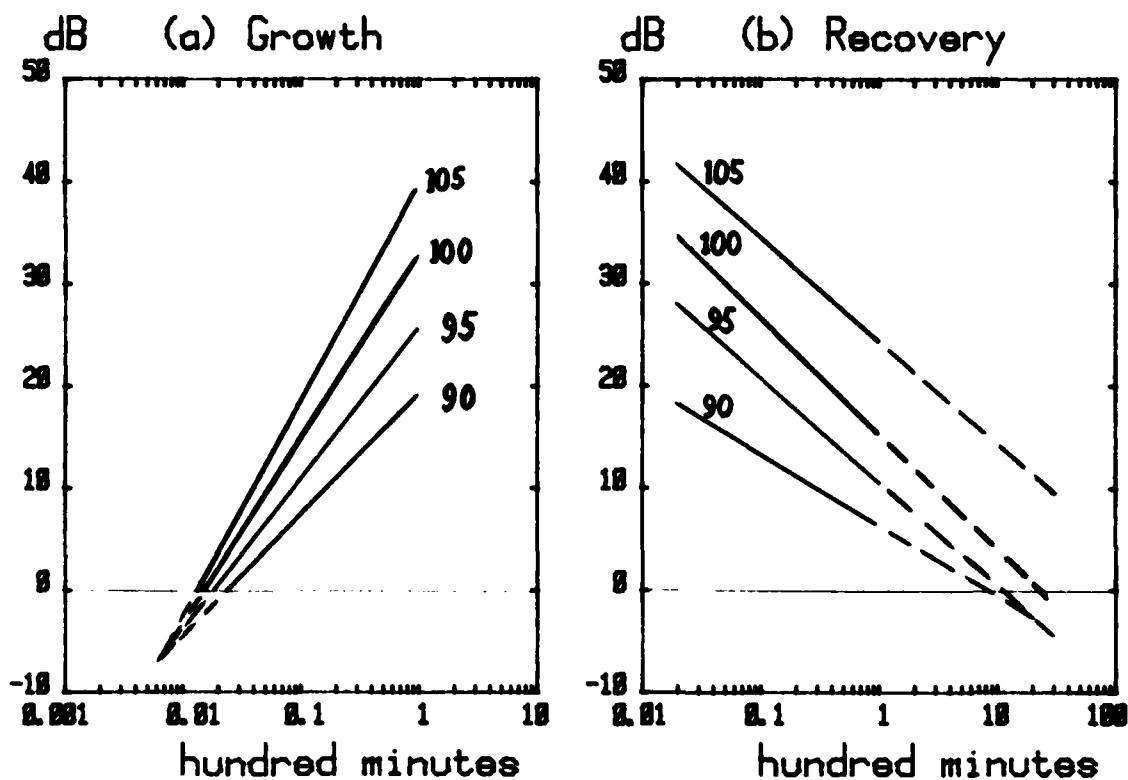


Fig 13a&b Average growth and recovery for different exposure levels (after Ward *et al*, Ref 6)

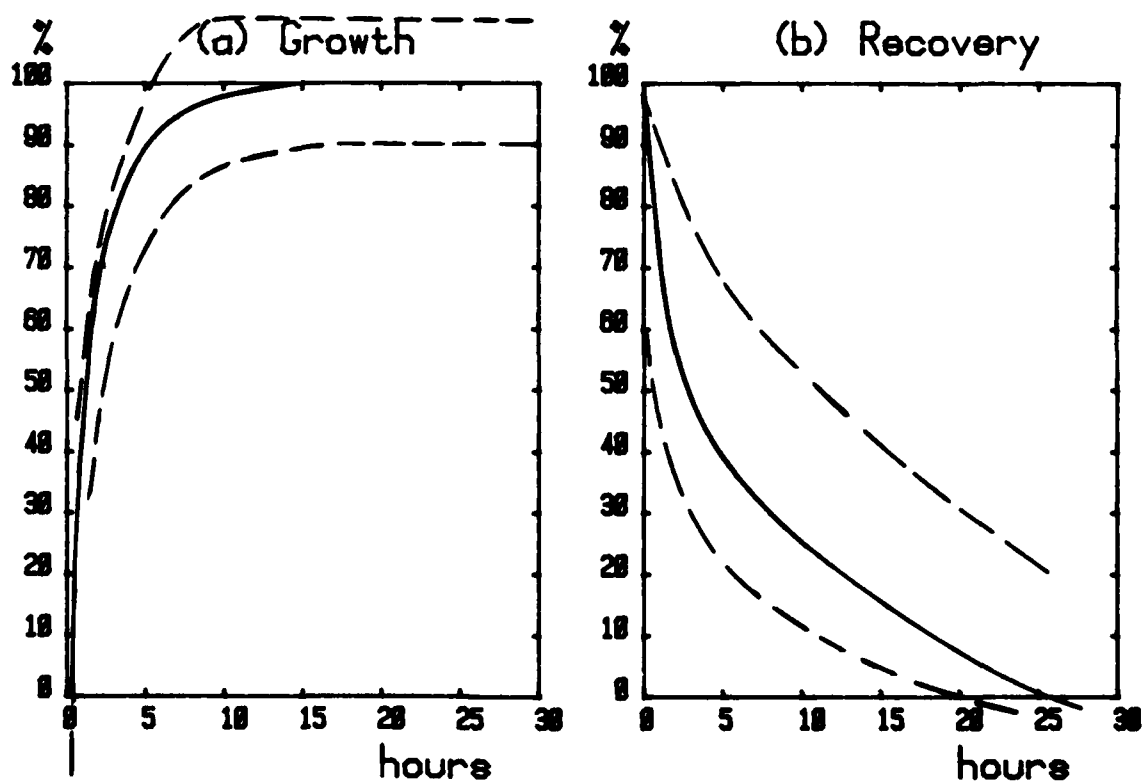
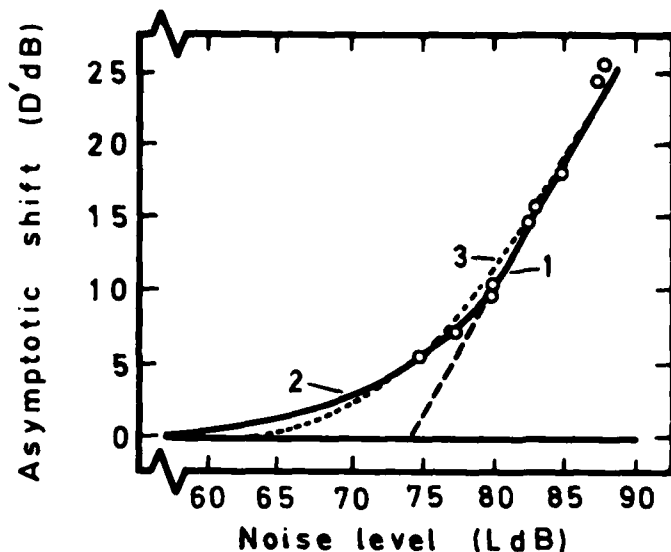


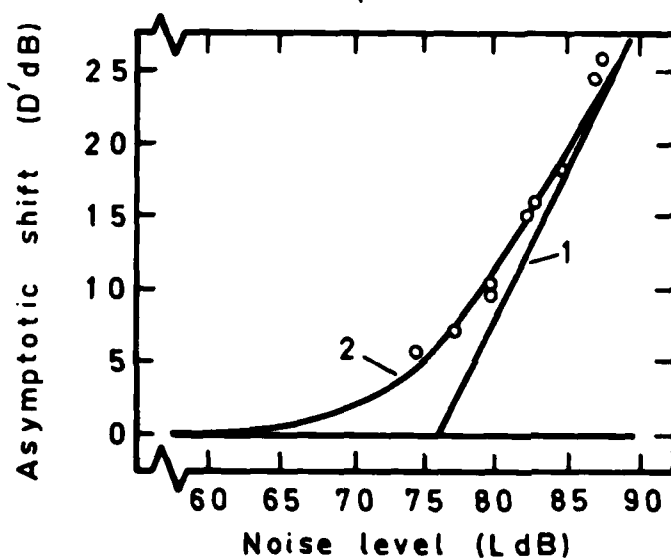
Fig 14a&b Average growth and recovery (after Mills *et al*, Ref 8)

Fig 15



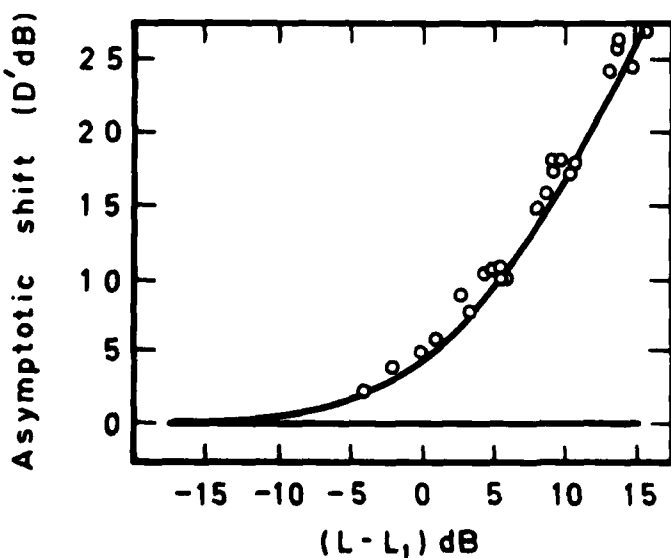
a Exponent: 1.7

1. $D' = 1.7(L - 74) \frac{L-74}{10}$
- 2 & 3. $D' = 17 \log(1 + 10^{\frac{L-74}{10}})$
2. According to ref 8
3. Actual
- Experimental data



b Exponent: 2

1. $D' = 2(L - 76) \frac{L-76}{10}$
2. $D' = 20 \log(1 + 10^{\frac{L-76}{10}})$
- Experimental data



c Exponent: 2 (normalized)

- $$D' = 20 \log(1 + 10^{\frac{L-L_1-2}{10}})$$
- Experimental data

Fig 15 Average ultimate TTS (data after Mills et al ref 9)

REPORT DOCUMENTATION PAGE

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5. DRIC Code for Originator 7673000W		6. Originator (Corporate Author) Name and Location Royal Aircraft Establishment, Farnborough, Hants, UK			
5a. Sponsoring Agency's Code N/A		6a. Sponsoring Agency (Contract Authority) Name and Location N/A			
7. Title Towards a better understanding of temporary threshold shift of hearing.					
7a. (For Translations) Title in Foreign Language					
7b. (For Conference Papers) Title, Place and Date of Conference					
8. Author 1. Surname, Initials Maslen, K.R.	9a. Author 2	9b. Authors 3, 4		10. Date March 1980	Pages 48
				Refs. 10	
11. Contract Number N/A	12. Period N/A	13. Project		14. Other Reference Nos.	
15. Distribution statement (a) Controlled by – (b) Special limitations (if any) –					
16. Descriptors (Keywords) (Descriptors marked * are selected from TEST) Temporary threshold shift. Hearing.					
17. Abstract It was thought that Temporary Threshold Shift of hearing due to exposure to noise might be more easily understood if the shifts were considered in terms of the rms pressure rather than in dB. Therefore, the forms to be expected if the rate of shift of the pressure threshold were proportional to the difference between itself and the ultimate threshold were calculated, and compared with a limited selection of published data. Good agreement with data for the growth of TTS in individuals was found, and moderately good agreement with recovery. Agreement with data on intermittent exposures was poor, but this may be due in part to the fact that only averaged data have been found, and averaging the widely disparate figures obtained for individuals may mask the true effects. It is also shown that the maximum ultimate TTS due to exposure to noise may be simply related to the mean square pressure of that noise. Further consideration of the mass of published work is needed, but this study suggests that at least some facets of TTS can be simply described in terms of exponential pressure shifts.					

