HEARING PROTECTORS

A dilemma involving acoustics and personal safety

A Thesis submitted in two volumes

for the degree of Doctor of Philosophy

in the University of Aston in Birmingham

by

Dennis Else

Department of Safety and Hygiene,

The University of Aston in Birmingham,

Gosta Green,

Birmingham B4 7ET.

October, 1976

VOLUME 2

VOLUME TWO CONTENTS

cont'd

cont'd

APPENDIX I

APPENDIX I

HEARING PROTECTOR SELECTION PROCEDURES

Introduction

Hearing protectors are worn to reduce the risk of occupational deafness. The reduction in risk is achieved by reducing the sound level at the ears whilst the hearing protectors are worn.

Hearing protectors do not attenuate sound by the same amount at all frequencies; neither do they provide the same attenuation on each occasion that they are worn. The attenuation provided by any hearing protector is a function of both the frequencies of the noise in which it is worn and the fit of the hearing protector on the wearer's head.

Within the audible frequency range, sound reaches the occluded ear by:

(i) transmission through leaks around the protector

(ii) vibration of the protector on the compliance provided by the skin and tissue layers that support the protector and the air that the protector encloses

(iii) deformation of the materials of the protector

(iv) transmission via the bone structure of the head.

Three of these mechanisms are dependent on the positioning of the protector on the head and on the anatomical dimensions of the head on which the protector is worn.

Procedures for the selection of hearing protectors have evolved in parallel with the criteria for limiting unprotected exposure to noise. All of the selection procedures have attempted to take into account the frequency dependence of attenuation and many selection procedures have also attempted to take into account variations in attenuation with fit.

This appendix describes and explores the assumptions that are made in the selection of hearing protectors.

Selection Procedures Applied at Individual Octave Bands

Prior to the appearance of single figure frequency-weighted hygiene standards, most methods of estimating the risk of occupational deafness were based on noise measurements expressed in octave bands.

In 1954 the report of the Royal Air Force Flying Personnel Research Committee (Dickson *et al*., 1954) recommended that unprotected ears should not be exposed to sound levels greater than 85dB per critical band. This recommendation was based on Kryter's work (1950)*. The method developed by Dickson and his colleagues for the selection of protectors is illustrated in Table I-I.

As can be seen from Table I-I, the maximum permitted sound level per critical band was adjusted to take into account the difference between the widths of the critical bands and the corresponding octave bands. The adjustments

* quoted by Dickson *et al*.

TABLE 1-1

A Selection Procedure Applied at Individual Octave Bands - An Example taken from Dickson et al., (1954)

Mid-Band Frequency (Hz)	Permitted Maximum SPL per Critical Band (dB)	Tolerable SPL per Octave Band (without protection) (dB)	Minimum Attenuation Afforded by MKVI Earmuffs in 98% of Subjects (dB)	Tolerable SPL per Octave Band when wearing MKVI Earmuffs (dB)
250	85	90	0	90
500	85	93	8	101
1000	85	95	15	110
2000	85	96	26	122
3000	85	96	31	127
4000	85	96	37	133
8000	85	94	30	124

provided octave band sound levels beyond which unprotected ears should not be exposed. These were denoted as the 'tolerable sound pressure levels' for each octave band. (Strictly, these should have been denoted "tolerable sound levels".) The estimates of the attenuation provided by the hearing protector were added to the corresponding 'tolerable sound pressure levels' to provide octave band sound levels above which the protector was not considered adequate protection. On the basis of this method, Dickson and his colleagues considered the RAF Mark VI earmuff adequate protection against any noise for which the octave band sound levels did not exceed the values given in the last column of Table I-I.

The attenuation data that were used in the selection procedure were obtained by Dickson and his colleagues by binaural free field threshold measurements at single frequencies - one mid-band frequency per octave. These were considered to be adequate predictors of the attenuation provided for all other frequencies within the corresponding octave bands. The stated aim of the selection procedure was the protection of 98 percent of wearers of the hearing protectors; to this end, the attenuation estimate used for each octave band was the mean of twenty threshold measurements (one per subject) minus twice the standard deviation of the

the measurements at that frequency.

Piesse, Rose and Murray (1962) based their selection procedure on the noise exposure limits recommended by the American Standards Association (1954)*. They aimed to ensure that persons were not exposed to noise levels in excess of 85dB in any of the octaves: 300-600Hz, 600-1200Hz, 1200-2400Hz and 2400-4800Hz. Piesse's selection procedure consisted of subtracting the attenuation estimate for the protector from the corresponding octave band and then comparing the result with 85dB.

The attenuation estimates that Piesse used were the mean of measurements made by a binaural free field threshold test at each octave mid-band frequency within the range 250Hz to 4000Hz. The attenuation was tested on ten subjects, each subject being tested once at each mid-band frequency.

Piesse did not comment on the percentage of wearers who would be protected; neither did he take account of individual variations from the mean attenuation. However, in a later report (Piesse, 1962) he stated that 50 percent of people using the hearing protectors chosen in the above manner might not be adequately protected.

Michael (1965) and Coles (1969) both used selection procedures based on octave bands. Michael did not mention any correction to take account of variation in attenuation with

---

* quoted by Piesse (1962)

fit but Coles recommended using attenuation estimates derived by subtracting one or two standard deviations from the means of the attenuation data at each octave mid-band frequency.

Selection Procedures Based on A-Weighted Sound Levels

Robinson (1968) showed that frequency-weighted sound energy is an appropriate parameter for the prediction of injury to hearing resulting from habitual exposure to continuous noise. The fundamental consideration is the A-weighted sound energy received cumulatively by the ears of the people who are exposed.

The energy rule has formed the basis of standards produced by: the British Occupational Hygiene Society (1971); the International Organisation for Standardisation (1971); and the Department of Employment's Code of Practice (1972).

The British Occupational Hygiene Society Standard does not provide a system for selecting hearing protectors.

However, the Department of Employment and the International Organisation for Standardisation recommendations provide similar procedures for estimating the A-weighted sound level at the ears when hearing protectors are worn.

The calculation effectively reduces to:

$$L_A = 10 \log \sum_{x=63}^{8000} 10^{\frac{(L_x - W_x - A_x)}{10}}$$

Equation 1-1

where L_A is the estimated A-weighted sound level at the occluded ears; L_x is the ambient octave band sound level for the octave centred at x hertz; W_x is A-weighting correction at x hertz; and A_x is the attenuation estimate for the octave band centred at x hertz.

The recommendation from the International Organisation for Standardisation does not define the attenuation estimate that should be used in the calculation but the Department of Employment's Code advocates the use of either the lower quartile attenuation, or the mean attenuation minus one standard deviation. The Code states that these attenuation estimates should have been obtained by threshold tests and that hearing protectors should normally be selected so that the sound level at the user's ears is always effectively reduced to 90dB(A) or less. However, no indication is made in the Code, of the proportion of a population for whom this aim would be achieved if the recommendations were followed. The Code does not comment on the 16 percent or 25 percent of occasions on which the hearing protectors might be worn without reducing the sound level at the user's ears to 90dB(A) or less if the Code's advice was followed.

The Draft Australian Code of Practice (Australian Standards Association, 1972) also recommends the use of a selection procedure for which Equation 1-1 is relevant. The

Australian Code recommends the use of the mean attenuation minus one and a half standard deviations. It states that the use of these attenuation estimates will ensure that 90 percent of the wearers will obtain at least the calculated amount of protection.

Table 1-2 illustrates the application of the Department of Employment's selection procedure for the simple case where the noise level is constant and the exposure duration is eight hours per day. The example is also illustrated graphically in Figure 1-1.

The noise spectrum used in the example was produced by an electric motor. The attenuation estimates that have been used are mean minus one standard deviation data for earmuffs. The reduction in noise level provided by the earmuffs in this example is 20dB(A). Where either the noise level is not constant, or the duration of exposure is not for eight hours per day, equivalent-continuous octave band sound levels must be used in Equation 1-1.

The implications of Equation 1-1 for the selection of hearing protectors for a particular application are often not recognised by those who select hearing protectors in industry. They may instead seek a universal figure for the A-weighted reduction provided by a particular hearing protector.

The necessity of applying Equation 1-1 is clearly

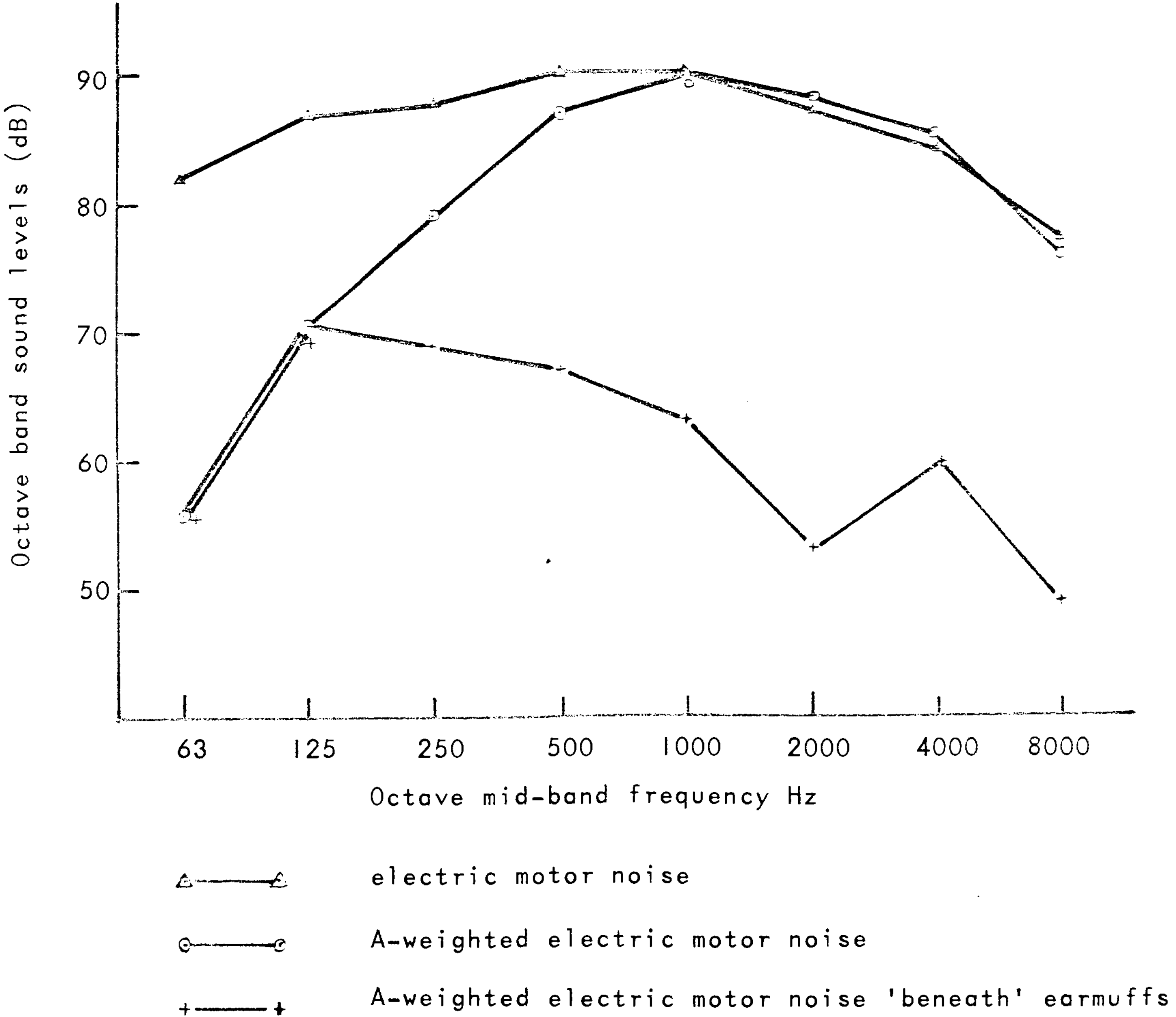
TABLE I-2

Selection Procedure Based on A-Weighted Sound Levels - an Example of the Attenuation Data for an Earmuff Applied to the Noise from an Electric Motor

	63	125	250	500	1000	2000	4000	8000	Overall sound level db(A)
Octave band sound levels: noise from electric motor (dB)	82	87	88	90	90	87	84	77	
A-Weighting corrections (dB)	-26	-16	-9	-3	0	1	1	-1	
A-Weighted Octave band levels: noise from electric motor dB(A)	56	71	79	87	90	88	85	76	94
Attenuation data for earmuff: mean minus standard one deviation (dB)	-	-	11.5	20	27	35	25	27	
A-Weighted Octave band levels 'beneath' earmuff dB(A)	56	71	68	67	63	53	60	49	74

FIGURE 1-1

Mean Minus One Standard Deviation Attenuation Data for Earmuffs Applied to the noise spectrum Produced by an Electric Motor



demonstrated by Figure 1-2, which shows the vast variations in A-weighted reductions provided by glass down earplugs in industrial noise spectra. Lower quartile attenuation data for glass down earplugs, from attenuation tests described in Appendix II, have been applied individually to 2640 industrial noise spectra (Appendix V) and the resulting A-weighted reductions displayed as a cumulative distribution.

For 50 percent of the noise spectra the estimated reduction in sound level provided by the earplugs was greater than 10dB(A). However, less than 6dB(A) reduction was found with at least 5 percent of the spectra, whilst greater than 17dB(A) reduction occurred with another 5 percent of the spectra.

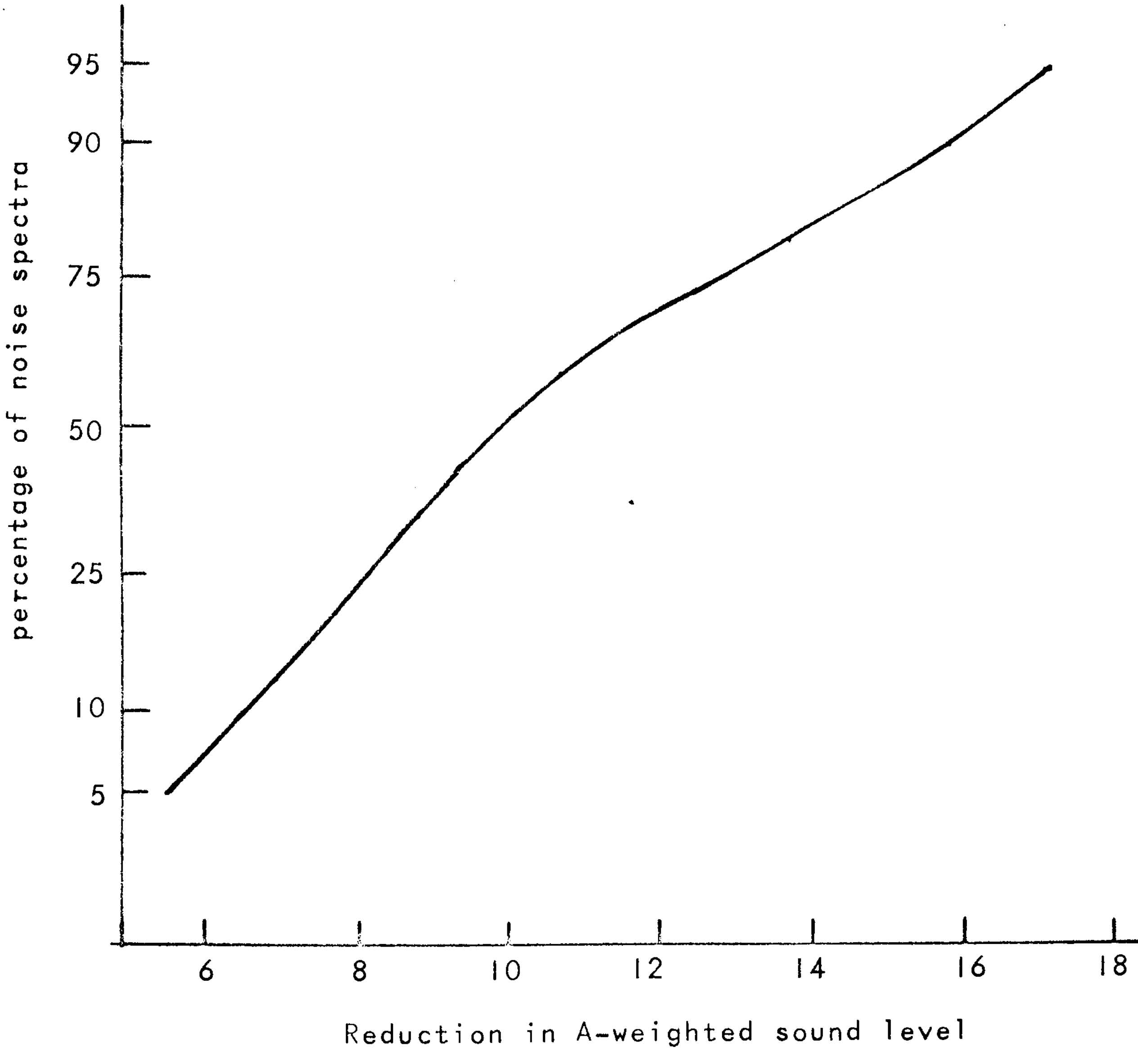
Clearly, a universal estimate of the A-weighted reduction provided by a hearing protector cannot be given - they might be worn in the high frequency noise produced by the sawing of aluminium and reduce the level by 17dB(A); or beside the intake to a compressor and reduce the level by only 5dB(A).

Assumptions Used in Selection Procedures Based on A-Weighted Sound Energy

The selection procedures attempt to estimate the A-weighted sound level at the ears of people wearing hearing protectors. As has been shown previously, the first step in the procedure consists of obtaining estimates of the A-weighted

FIGURE 1-2

Cumulative Distribution of the Reduction in A-Weighted Sound Level Afforded by Glass Down Earplugs in 2640 Industrial Noise Spectra; based on Lower Quartile Attenuation Data



octave band sound levels from measured octave band sound levels; these are obtained by subtracting single frequency A-weighting corrections at the corresponding mid-band frequencies. Clearly, the A-weighting corrections are single frequency corrections, whilst the octave band sound levels are octave band measurements. This would not produce errors if both the sound level and the appropriate corrections are constant for all frequencies within any octave band; neither would errors result if the gradient of the sound level-frequency spectrum is identical in magnitude and sign to the gradient of the A-weighting correction curve within the corresponding octave band. If, however, the gradients of the sound level spectrum and the A-weighting curve are not identical, then calculations of the A-weighted octave band sound levels will introduce errors.

The second step in the selection procedure consists of obtaining estimates of the A-weighted octave band sound levels at the ears when hearing protectors are worn; these are obtained by subtracting the attenuation measured at the corresponding octave mid-band frequencies. The attenuation estimate may have been obtained from attenuation tests with pure-tones, or third octaves of random noise. If the gradients of the A-weighted sound level spectrum and the attenuation spectrum are not identical in magnitude and sign within the corresponding octave errors are likely to be introduced.

The third step in the selection procedure is the addition of the A-weighted octave band sound levels in order to obtain an estimate of the overall A-weighted sound level at the ears when hearing protectors are worn. The attenuation estimates used in the calculations are the n centiles of the attenuation data at each frequency. It is therefore assumed that the calculated A-weighted sound level at the occluded ears will only be exceeded on n percent of the occasions on which the hearing protectors are worn.

The selection procedure therefore assumes that the distributions at all frequencies are directly related; that is, the upper tails of the distributions at all frequencies consist of measurements made on the same subjects on the same occasions. If this is not true in practice, then the reduction in sound level provided by the hearing protector on any occasion will always be governed by those octave bands which permit the passage of the most A-weighted sound energy.

The selection procedures based on A-weighted noise dose, like those earlier procedures based on octave bands, assume that: the attenuation distributions are normal; and that the variance is produced by differences between the attenuation provided to the different people who wear the hearing protectors. The assumption of negligible within-subject variance has greater significance in these selection methods based on A-weighted dose. If on some occasions a person wearing hearing protectors receives high attenuation but on other occasions he receives low attenuation, the long-term result will be that the person will receive less protection than calculated by the selection procedures.

Since the A-weighted sound level at the ears is calculated from the octave bands 63Hz to 8000Hz only, the selection procedures assume that sound energy from frequencies above 11313Hz and below 44Hz does not contribute significantly to the A-weighted sound level at the ears when hearing protectors are worn.

The assumptions can be summarised briefly:

1. The attenuation measured at the octave mid-band frequency is assumed to be an adequate estimator of the attenuation provided for all other frequencies within the corresponding octave band and the A-weighting correction at the octave mid-band frequency is assumed to be an adequate estimator of the A-weighting corrections for all frequencies within the corresponding octave band
2. The attenuation at each frequency is assumed to follow a normal distribution
3. The major component of variance is assumed to be produced by differences between the attenuation

provided to the different people who wear the hearing protectors

4. The attenuation distributions at each frequency are assumed to be directly related to the distributions at all other frequencies
5. The within-subject variance is assumed to have negligible effect on the reduction in A-weighted sound energy calculated by the procedure
6. Sound energy from frequencies above 11313Hz and below 44Hz is assumed to make a neglible contribution to the A-weighted sound level at the occluded ears.

The Use of Octave Mid-Band Attenuation Values

The results of real-ear attenuation tests in which the attenuation at all third octaves has been measured are not available. However, Russell and May (1976) have published the results of objective attenuation tests in which they used an artificial head. Their results include attenuation estimates for all third octaves. The results for one pair of earmuffs are shown in Table 1-3.

As can be seen from Table 1-3, differences of up to six decibels exist between attenuation estimates within the same octave band. Similar differences were recorded with other earmuffs tested on the artificial head. Similar differences

TABLE 1-3

Reduction in A-Weighted Sound Level Provided by Earmuffs - Estimates from Three Third-Octave Attenuation Measurements per Octave Band

Third-octave mid-band frequency Hz	Third-octave band sound level dB Flat Spectrum	Third-octave band sound level dB Falling Spectrum	A-weighting correction dB	Earmuff* attenuation dB
50	100	100	- 30.2	7
63	100	97.3	- 26.2	8
80	100	94.7	- 22.5	7
100	100	92.0	- 19.1	6
125	100	89.3	- 16.1	7
160	100	86.7	- 13.4	9
200	100	84.0	- 10.9	11
250	100	81.3	- 8.6	14
315	100	78.7	- 6.6	17
400	100	76.0	- 4.8	19
500	100	73.3	- 3.2	22
630	100	70.7	- 1.9	24
800	100	68.0	- 0.8	28
1000	100	65.3	- 0	30
1250	100	62.7	+ 0.6	31
1600	100	60.0	+ 1.0	33
2000	100	57.3	+ 1.2	32
2500	100	54.7	+ 1.3	27
3150	100	52.0	+ 1.2	27
4000	100	49.3	+ 1.0	26
5000	100	46.7	+ 0.5	22
6300	100	44.0	- 0.1	25
8000	100	41.3	- 1.1	24
10,000	100	38.7	- 2.5	22

Estimated reductions in A-weighted sound level: flat spectrum = 23.2dB(A)
falling spectrum = 9.6dB(A)

* Data from Russell and May (1976) - third-octave attenuation measured with an artificial head.

were also present in the data Russell and May obtained by a semi-objective test in which microphones were embedded in the earmuffs.

Russell and May's data have been used to calculate the reductions in A-weighted level that could be expected from the earmuffs in a flat spectrum of noise and a 'fast falling' spectrum with a slope of eight decibels per octave. The A-weighted reductions have been calculated using all third octave attenuation estimates and also using only the third octaves centred at the octave mid-bands (Tables 1-3 and 1-4).

In the examples that have been chosen the inclusion of the other two third octaves in the calculation of A-weighted reduction has only slight effect (less than 0.5dB(A)).

However, the errors need not always be so small - the magnitude of the error depends upon the particular combination of noise spectrum and attenuation spectrum. Large errors could result if minima in the attenuation spectrum coincided with maxima in the noise spectrum.

Recent developments in semi-objective attenuation testing techniques (Rood, 1976), in which small microphones are placed inside earmuffs worn by subjects, may serve to quantify these errors. It may then be possible to measure the A-weighted sound level inside hearing protectors when they are worn in complex industrial noise spectra.

TABLE I-4

Reduction in A-Weighted Sound Level Provided by Earmuffs - Estimates from One Third-Octave Attenuation Measurement per Octave Band

Octave mid-band frequency Hz	Octave band sound level dB Flat Spectrum	Falling Spectrum	A-weighting correction dB	Earmuff* attenuation dB
63	105	102.6	- 26.2	8
125	105	94.6	- 16.1	7
250	105	86.6	- 8.6	14
500	105	78.6	- 3.2	22
1000	105	70.6	0	30
2000	105	62.6	+ 1.2	32
4000	105	54.6	+ 1.0	26
8000	105	46.6	- 1.1	24

Estimated reductions in A-weighted sound level:

flat spectrum = 23.6dB(A)
falling spectrum = 9.8dB(A)

* Data from Russell and May (1976) - third-octave attenuation measured with an artificial head.

Attenuation Assumed to be Distributed Normally

Earplugs

In an experiment to determine the attenuation provided by glass down earplugs I used a binaural free field threshold technique (American Standards Association z.24.22, 1957). The attenuation was measured at the seven octave mid-band frequencies from 125 hertz to 8000 hertz. Each subject was tested six times at each of the test frequencies. The details of the experimental procedure and the results of the tests are given in Appendix II.

For the purpose of examining the shape of the distributions of attenuation at each frequency the data have been displayed in the form of cumulative distributions. The cumulative distribution for each test frequency is displayed in figures 1-3 to 1-9.

Also shown in figures 1-3 to 1-9 are the normal distributions predicted from the means and the standard deviations at each test frequency. At no frequency is there a significant difference between the predicted and observed cumulative distribution.
(Kolmogorov - Smirnov one-sample two-tailed test with significance level of P = 0.05.)*

---

*Siegel (1956)

FIGURE I-3

Cumulative Distribution of Attenuation Measurements for Glass Down Earplugs at 125Hz Compared with the Normal Distribution Predicted from the Mean and Standard Deviation

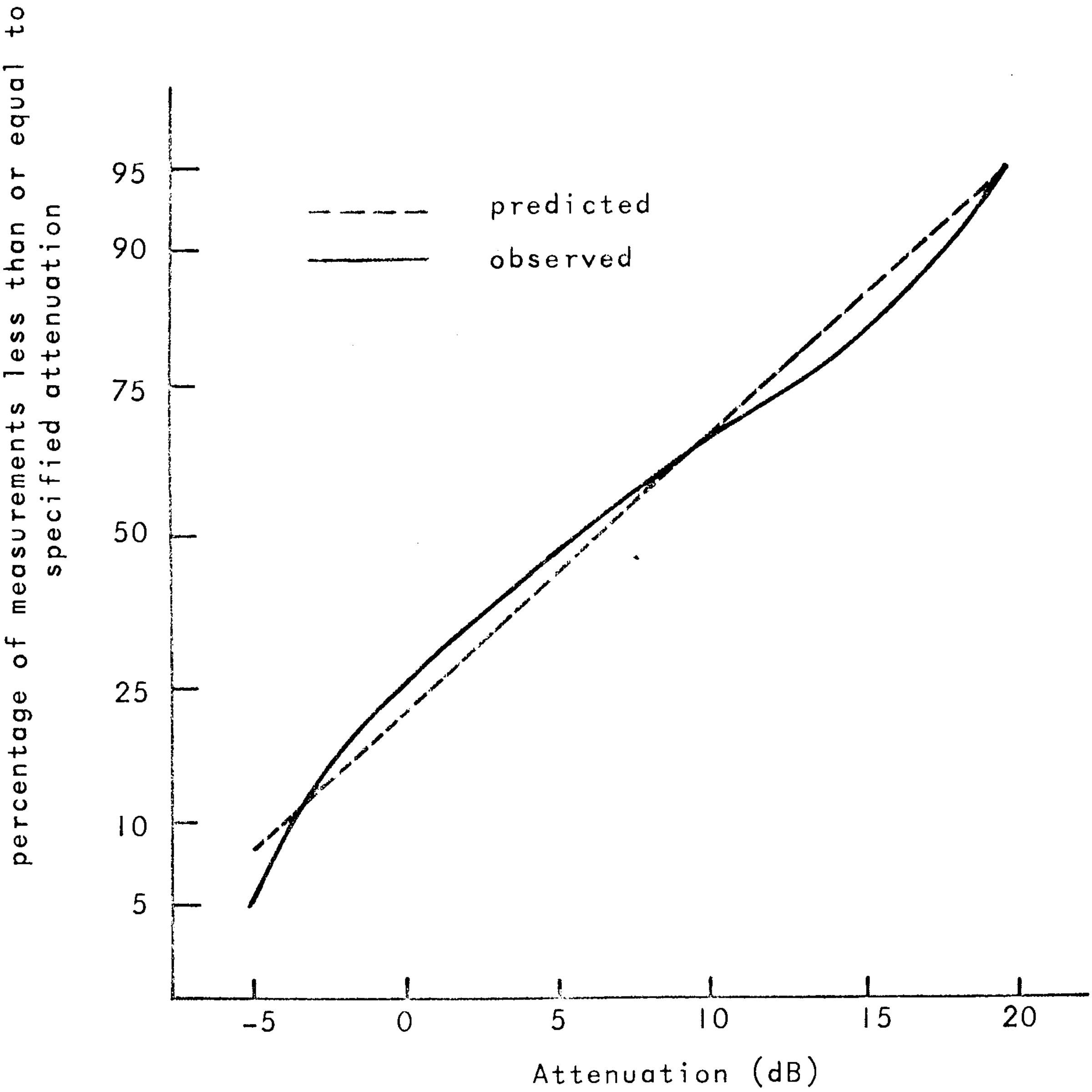


FIGURE 1-4

Cumulative Distribution of Attenuation Measurements for Class Down Earplugs at 250Hz Compared with the Normal Distribution Predicted from the Mean and Standard Deviation

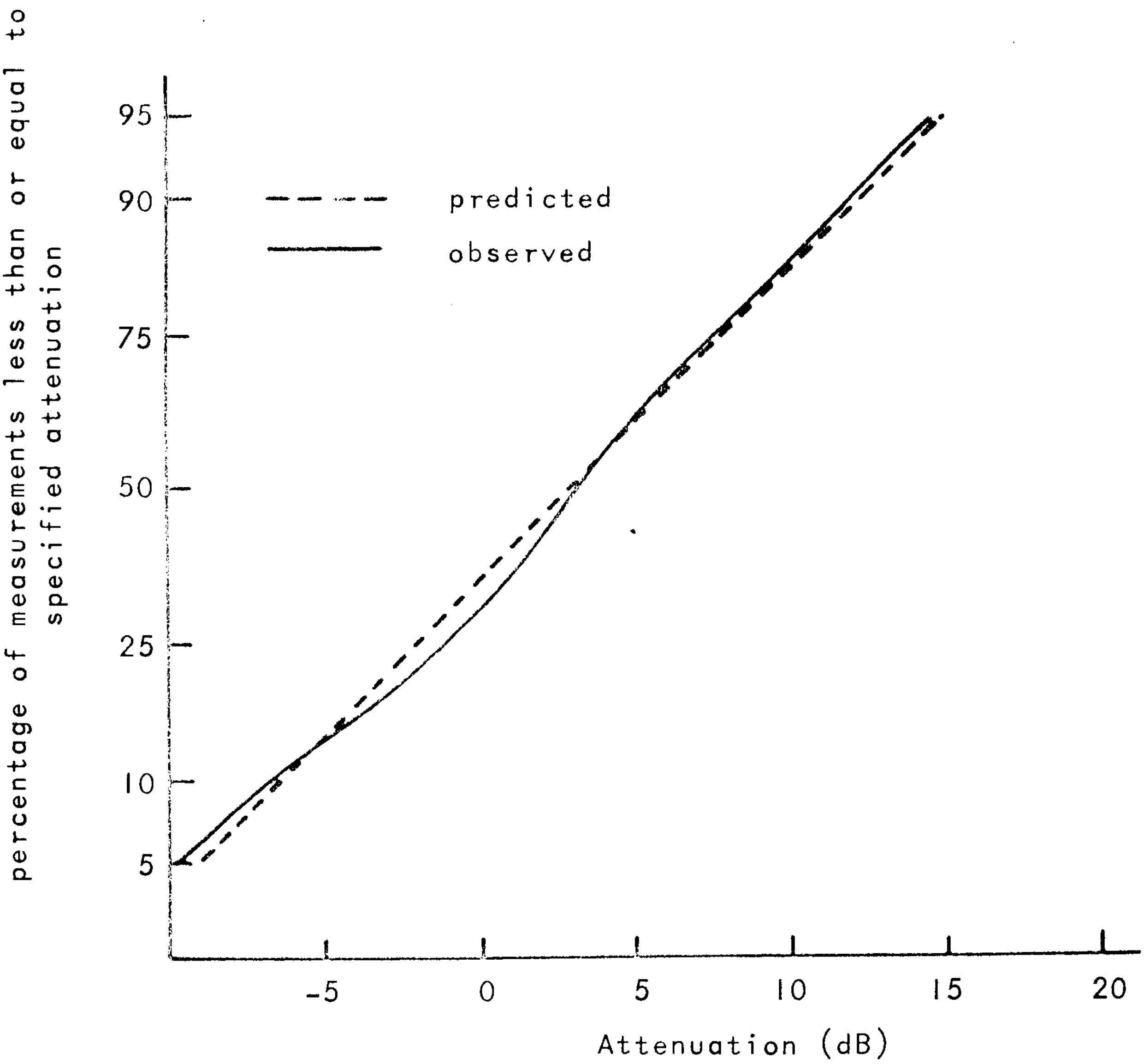


FIGURE I-5

Cumulative Distribution of Attenuation Measurements for Glass Down Earplugs at 500Hz Compared with the Normal Distribution Predicted from the Mean and Standard Deviation

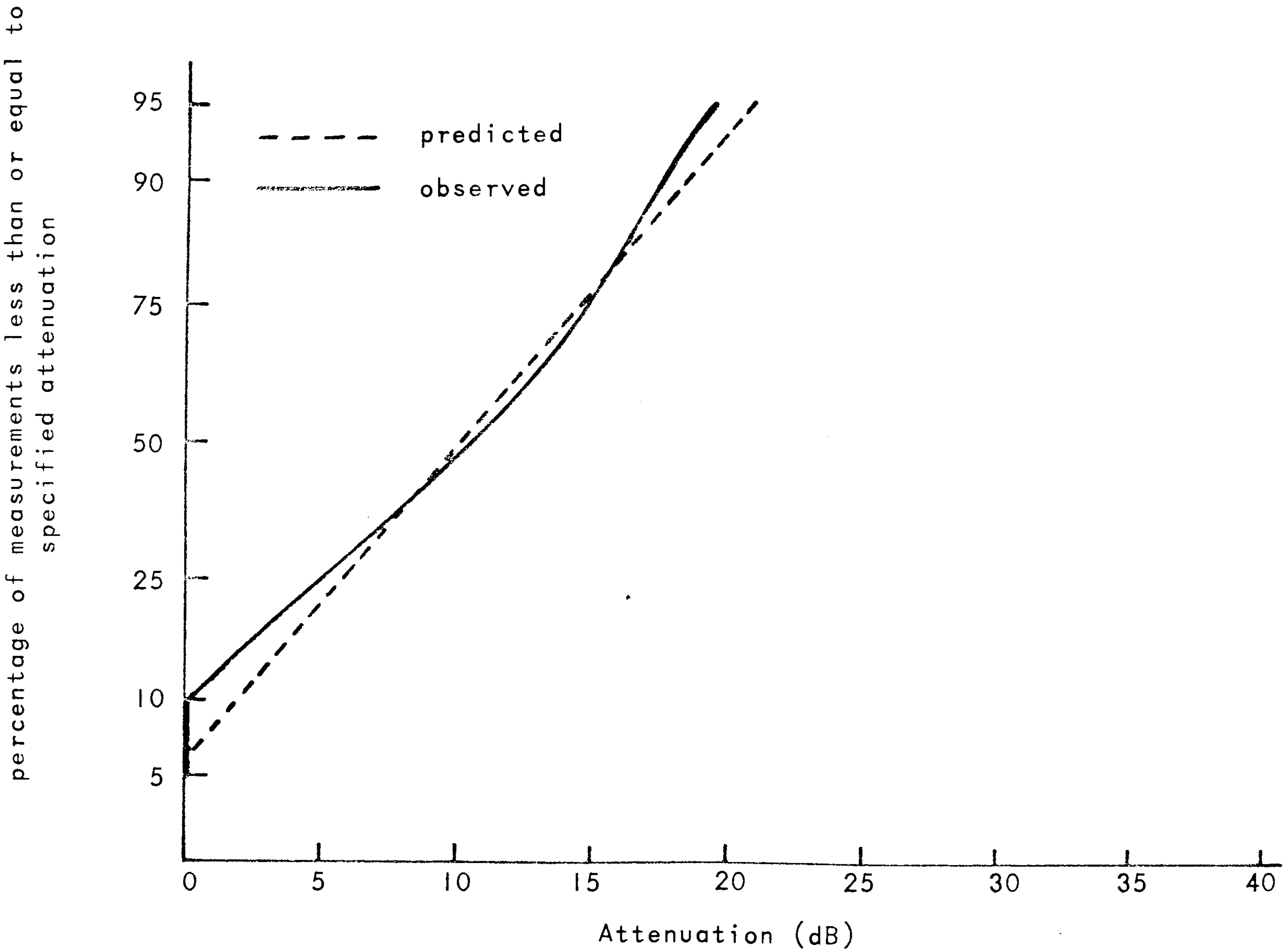


FIGURE 1-6

Cumulative Distribution of Attenuation Measurements for Glass Down Earplugs at 1000Hz Compared with the Normal Distribution Predicted from the Mean and Standard Deviation

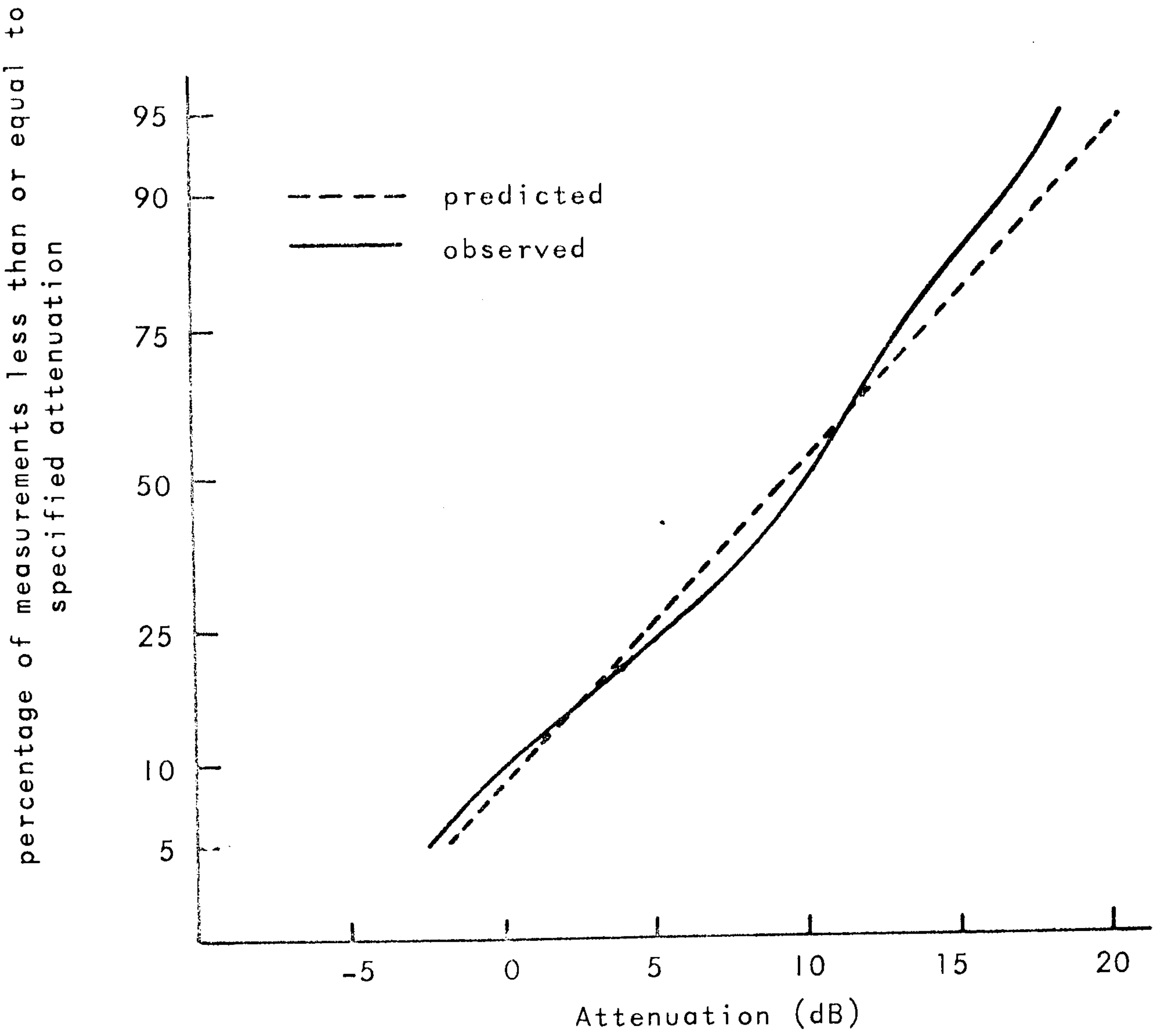


FIGURE 1-7

Cumulative Distribution of Attenuation Measurements for Glass Down Earplugs at 2000Hz Compared with the Normal Distribution Predicted from the Mean and Standard Deviation

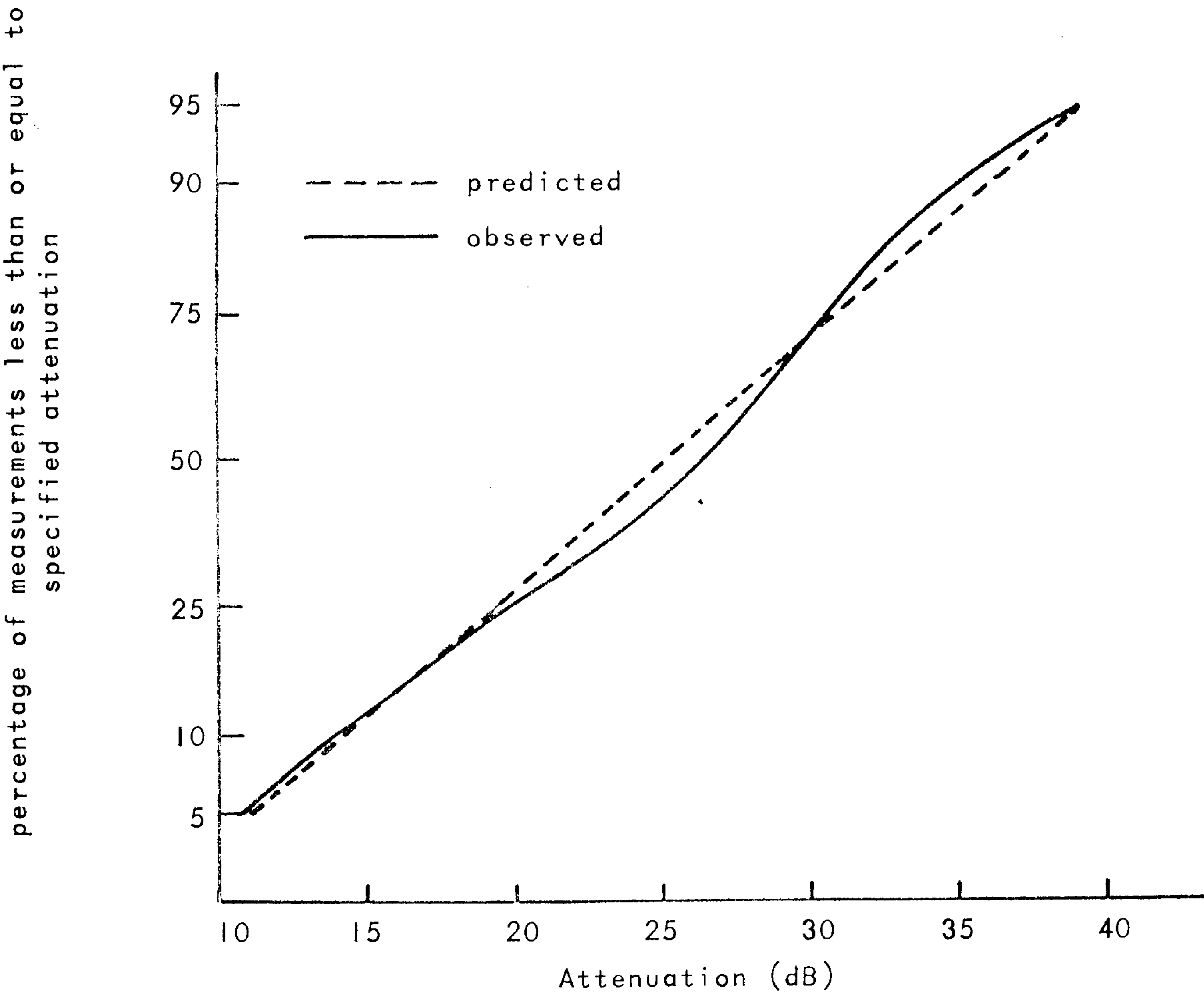


FIGURE I-8

Cumulative Distribution of Attenuation Measurements for Glass Down Earplugs at 4000Hz Compared with the Normal Distribution Predicted from the Mean and Standard Deviation

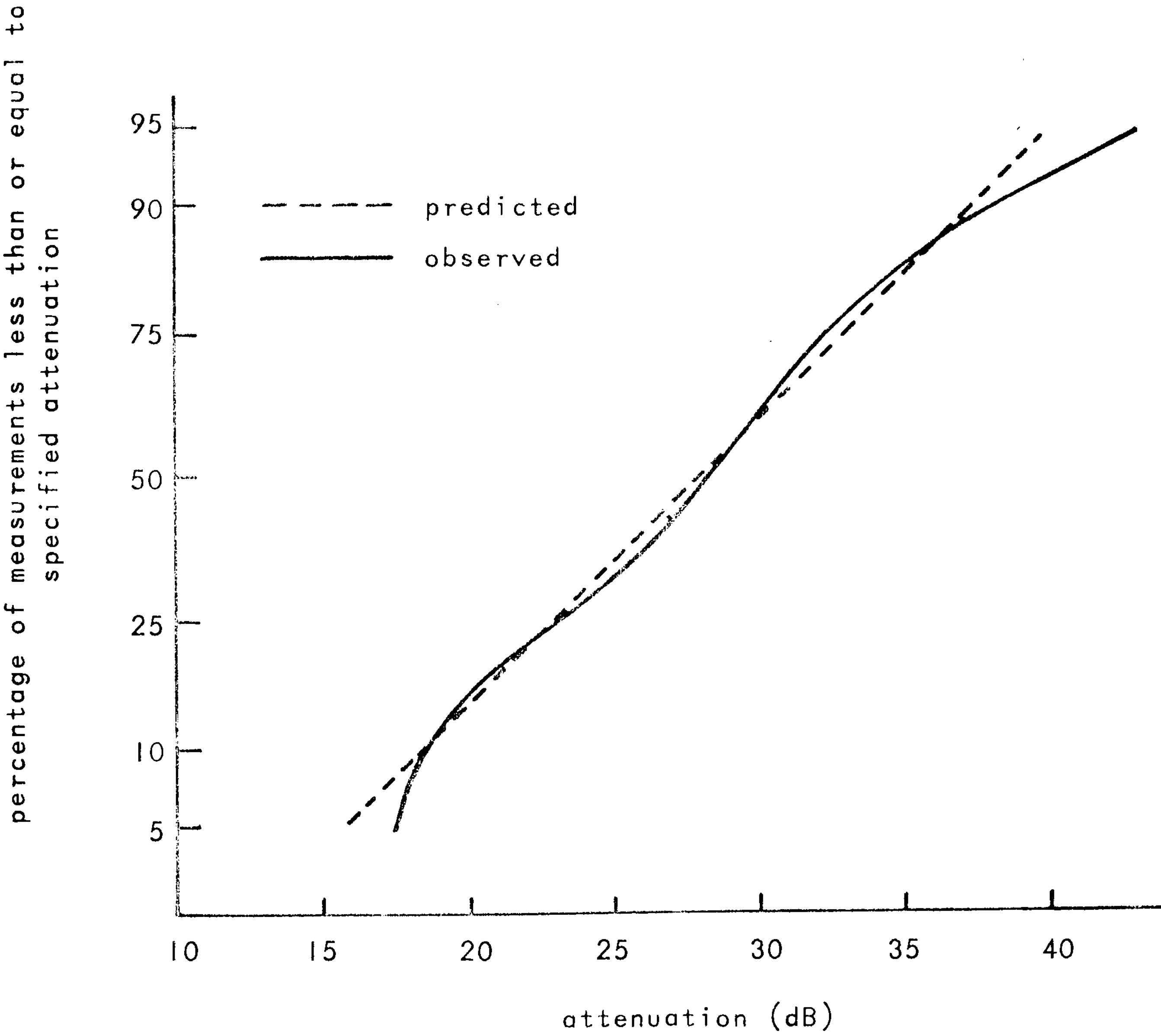
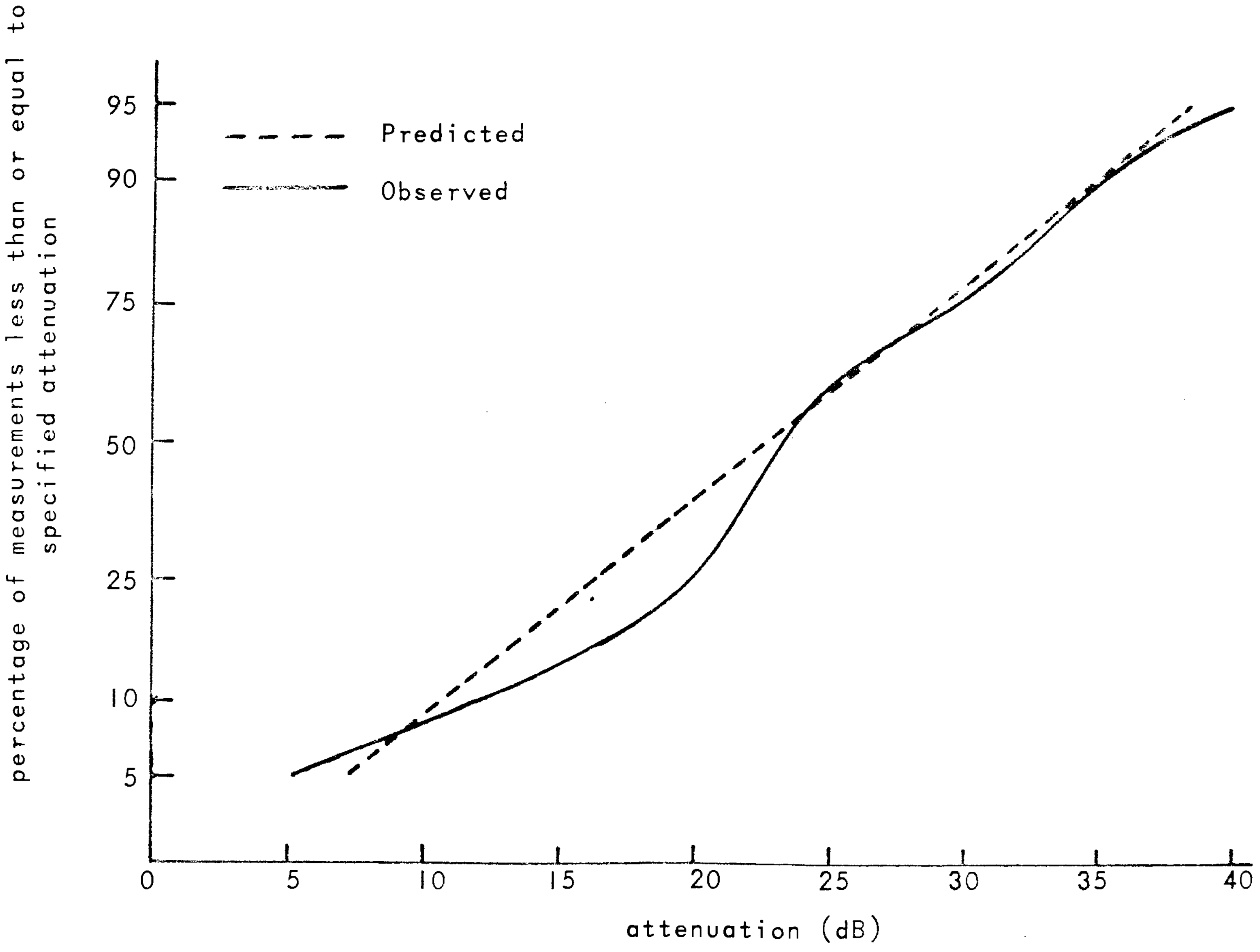


FIGURE I-9

Cumulative Distribution of Attenuation Measurements for Glass Down Earplugs at 8000Hz Compared with the Normal Distribution Predicted from the Mean and Standard Deviation



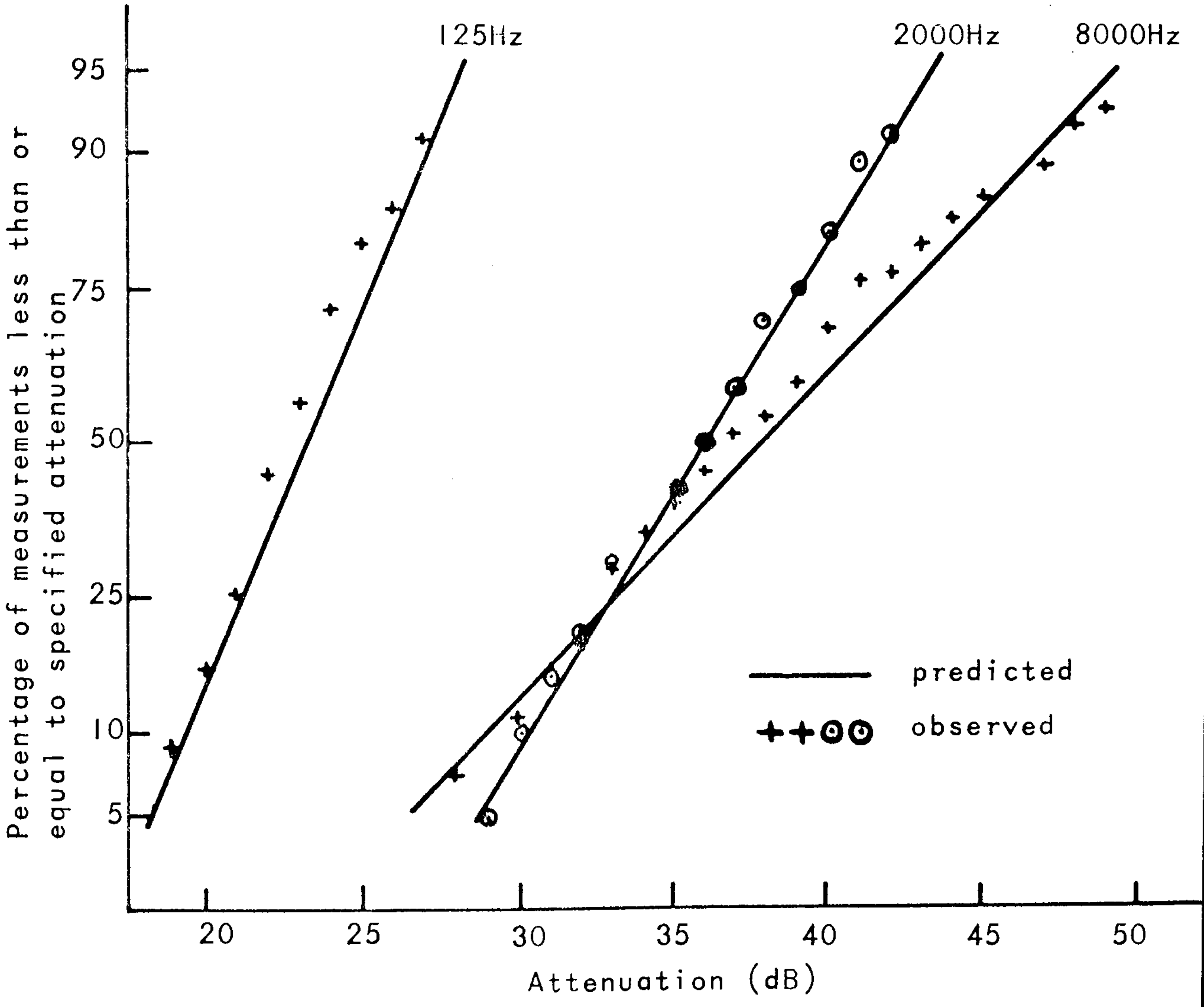
Hanson and Blackstock (1958) investigated the attenuation provided by V51-R earplugs. They were of the opinion that the data were distributed 'roughly normally' but they did not provide statistical evidence to support their opinions. In figure 1-10 the results of their five measurements at 125Hz on each of twenty subjects are displayed in the form of a cumulative distribution. The normal distribution predicted from the data is also shown.

Hanson and Blackstock also measured the attenuation at 250Hz, 500Hz, 1000Hz, 2000Hz, 3000Hz, 4000Hz, 6000Hz and 8000Hz. Figure 1-10 shows the cumulative distributions and predicted normal distributions for the 2000Hz and 8000Hz data. All distributions of attenuation measurements do not differ significantly from normal distributions.
(Kolmogolov - Smirnov one-sample two-tailed tests with significance level of $P = 0.05$.)

The attenuation measurements for the glass down earplugs were obtained using a test procedure in which the subjects fitted the earplugs themselves; this resulted in a large variance in the resultant distributions (range $39.7dB^2$ to $88.4dB^2$). The attenuation measurements on the V51-R earplugs were obtained using a procedure in which the fitting of each earplug was supervised by the experimenters; this resulted

FIGURE 1-10

Cumulative Distributions of Attenuation Measurements for V51-R earplugs at 125Hz, 2000Hz and 8000Hz Compared with Normal Distributions Predicted from Means and Standard Deviations



in distributions of attenuation having much smaller variance (range 9.3dB^2 to 46.6dB^2). Although the spread of the distributions for the two earplug experiments were vastly different, I have not been able to demonstrate a significant departure from normality.

Earmuffs

Dickson and colleagues from their measurements with earmuffs (Dickson *et al.*, 1954) concluded that for some earmuffs at low frequencies the distributions were skew. They did not provide statistical evidence for this conclusion but gave as an example results from measurements on the Acoustics Laboratory Mk VI earmuff at 250Hz. They stated that the lowest attenuation recorded for this device was zero decibels, yet calculation of the mean minus twice the standard deviation gave a negative value, from which they concluded that the distribution at 250Hz was skew. However, since the data for this attenuation frequency had a variance of 16dB^2 and a mean of 4dB, one would expect, on the basis of a normal distribution, that 16 percent of the results would take a value of zero decibels or less. In the sample of measurements taken, 5 percent (one measurement) took this value; the difference between the observed and the expected percentages is not sufficient evidence to conclude that the distribution is skew.

(A Kolmogorov - Smirnov one-sample two-tailed test at a significance level of 0.05 requires a maximum difference between the distribution of at least 29 percent.)

Martin (private communication, 1973) used a binaural threshold technique to measure the attenuation provided by two different types of earmuff. He used one-third octaves of random noise as the test signals and presented these from a tetrahedral array of loudspeakers. The results of the tests at 250Hz, 2000Hz and 8000Hz are displayed in Figures 1-11 and 1-12 in the form of cumulative distributions and are compared with the normal distributions predicted from the test data.

(Kolmogorov - Smirnov one-sample two-tailed tests applied to the distributions at the three frequencies have shown that the distributions of attenuation do not differ significantly from normal distributions.)

Attenuation data from tests with earplugs and earmuffs; pure tones and random noise; and supervised fitting and unsupervised fitting have been studied. I have found no evidence to disprove the assumption that attenuation follows a normal distribution.

The Between-Subject Variance in Attenuation Data

The attenuation provided by hearing protectors at any

FIGURE 1-11

Cumulative Distributions of Attenuation Measurements for Earmuff (Type I) at 250Hz, 2000Hz and 8000Hz Compared with the Normal Distributions Predicted from Mean and Standard Deviation

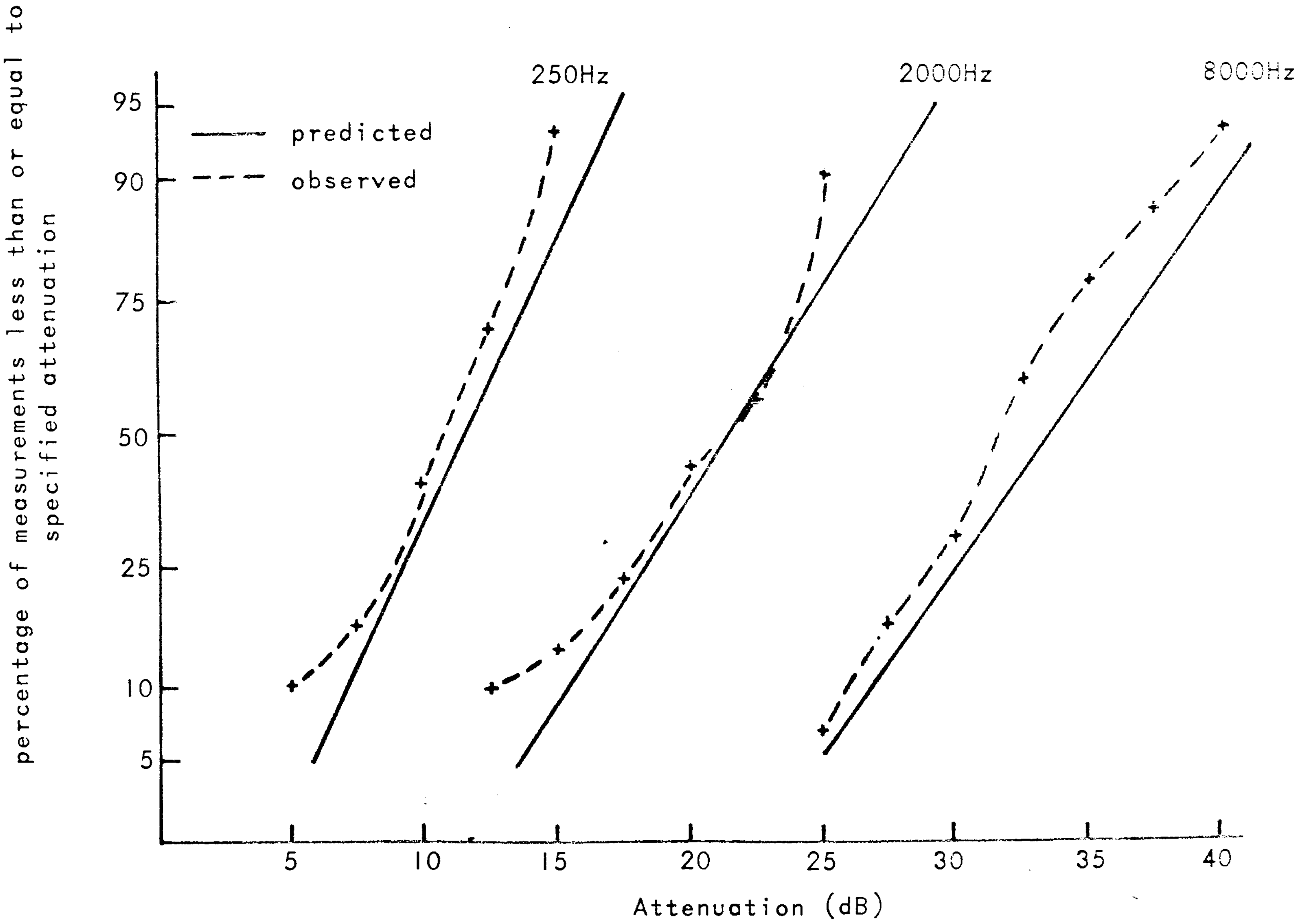
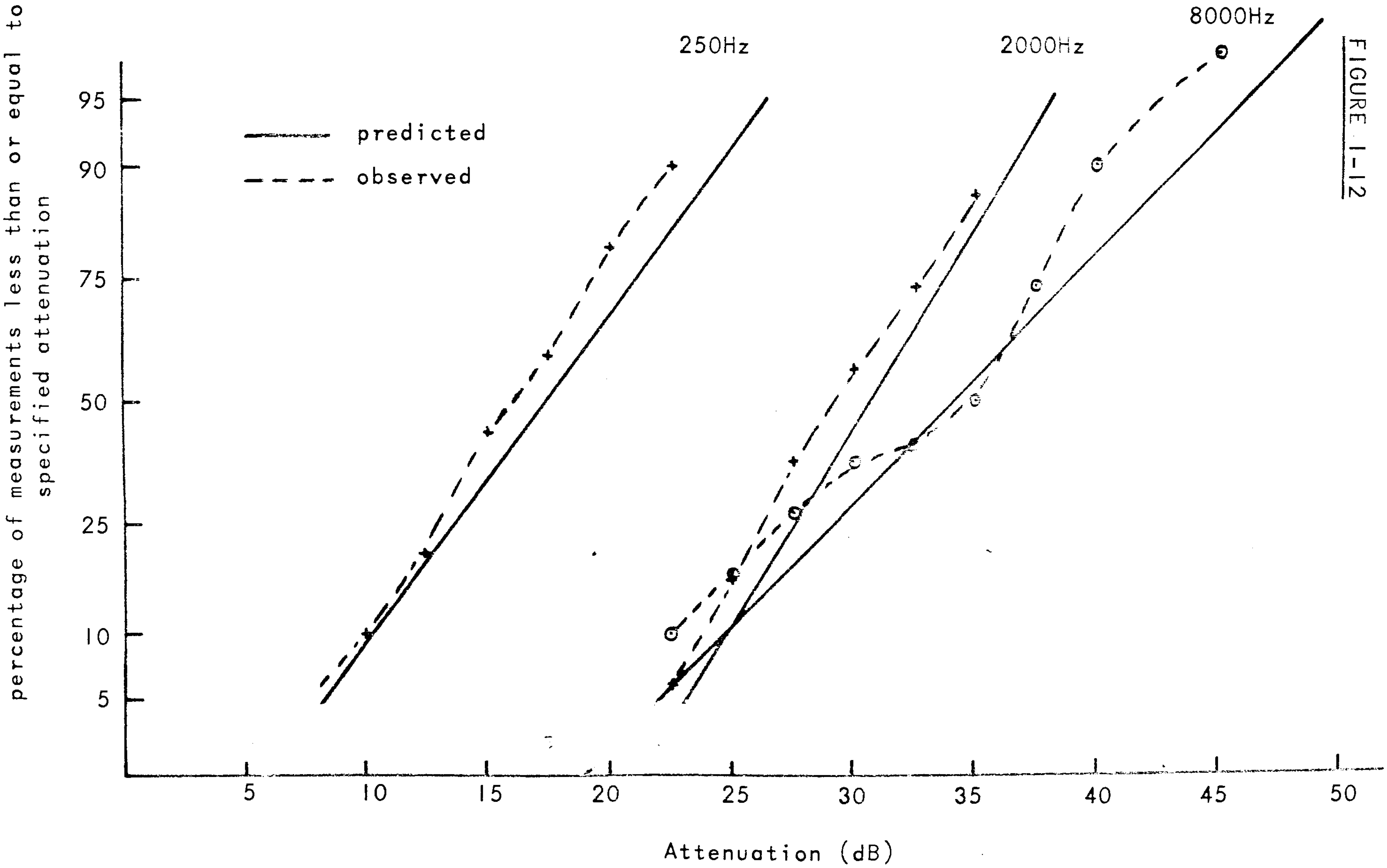


FIGURE I-12

Cumulative Distributions of Attenuation Measurements for Earmuff (Type 2) at 250Hz, 2000Hz and 8000Hz compared with the Normal Distributions Predicted from Mean and Standard Deviation



one frequency differs from occasion to occasion and from person to person.

The total variance of the attenuation at any one frequency can be considered to be a combination of:

(i) Between-subject variance - this will include variance produced by differences in head sizes and shapes; ear shapes and volumes; and skin and flesh compliances

(ii) Within-subject variance - this will include variance produced by the positioning of the hearing protector and the added effects of any adjustment inherent in the hearing protector.

Dickson and colleagues (1954) measured the attenuation provided by many different types of earmuffs using binaural free field threshold tests. The technique that they employed consisted of measuring the attenuation provided for 20 subjects on one occasion each. However, for two of the earmuffs, they also measured the attenuation provided for one subject on 20 separate occasions. The results obtained for these two earmuffs by both test methods are shown in Table I-5.

The total variance for the tests involving twenty subjects

TABLE I-5

Attenuation Measurements on Two Types of Earmuff: Twenty Subjects x One Measurement; and One Subject x Twenty Measurements (Dickson et al., 1954)

		Test Frequency hz 250	500	1000	2000	4000	8000
RAF MKVI EARMUFF							
20 subjects x 1 measurement	Mean attenuation dB	4	15	24	32	47	41
	Variance dB^2	16.0	10.9	18.5	8.4	23.0	29.2
1 subject x 20 measurements	Mean attenuation dB	9	15	28	38	52	40
	Variance dB^2	13.0	16.0	31.4	28.1	38.4	37.2
Significance of difference between variance estimates*		NS	NS	NS	S	NS	NS
NOSONIC MK II EARMUFF							
20 subjects x 1 measurement	Mean attenuation dB	2	11	18	25	37	36
	Variance dB^2	5.3	16.0	16.0	34.8	26.0	25.0
1 subject x 20 measurements	Mean attenuation dB	5	12	21	27	39	37
	Variance dB^2	24.0	36.0	23.0	31.4	26.0	26.0
Significance of difference between variance estimates*		S	NS	NS	NS	NS	NS

* NS = not significant at $p = 0.05$

S = significant at $p < 0.05$

must be composed of both between-subject and within-subject variance, whilst the total variance of the tests involving one subject cannot include any between-subject variance.

Since the differences between the variances obtained under the two test procedures only reach significance (P = 0.05) at one frequency for each earmuff, it must be concluded that the within-subject variance is a major contributor to the total variance at most of the test frequencies.

The results of a similar comparative study with two types of earplugs (Dickson *et al.*, 1954) are shown in Table I-6.

From the results obtained with V51-R earplugs the variances obtained under the two test methods were significantly different (P = 0.05) at more than half of the test frequencies.

From the results obtained with Mallock Armstrong earplugs the variances obtained under the two test methods were significantly different (P = 0.05) at only two of the test frequencies.

However, the within-subject variance in these cases could have accounted for a large proportion of the total variance of the measurements made on the twenty subjects.

TABLE 1-6

Attenuation Measurements on Two Types of Earplugs: Twenty Subjects x One Measurement; and One Subject x Twenty Measurements (Dickson et al., 1954)

		Test Frequency Hz 250	500	1000	2000	4000	8000
V51-R EARPLUGS							
20 subjects x 1 measurement	Mean attenuation dB	12	14	18	25	30	27
	Variance dB^2	70.6	50.4	84.6	86.5	121	121
1 subject x 20 measurements	Mean attenuation dB	14	17	17	33	35	30
	Variance dB^2	23.0	44.9	26.0	36.0	26.0	62.4
Significance of difference between variance estimates*		S	NS	S	S	S	NS
MALLOCH ARMSTRONG EARPLUGS							
20 subjects x 1 measurement	Mean attenuation dB	6	9	13	20	22	18
	Variance dB^2	65.6	72.2	127.7	121.0	139.2	74.0
1 subject x 20 measurements	Mean attenuation dB	7	6	14	30	29	21
	Variance dB^2	49.0	50.4	60.8	100.0	24.0	51.8
Significance of difference between variance estimates*		NS	NS	S	NS	S	NS

* NS = not significant at $p = 0.05$

S = significant at $p < 0.05$

Whilst at the other frequencies, it can be concluded that the within-subject variance is a significant contributor to the total variance.

The previous estimates of within-subject variance have been obtained from repeat measurements on only one subject in each case. A more comprehensive estimate of within-subject variance can be achieved when repeat measurements are made on each of a group of subjects; from which the variance can be analysed using a one-way analysis of variance using a variance components model.

Howell and Martin (1973) applied a variance components model to the attenuation data from attenuation tests on six different hearing protectors: three types of earplug each measured at two laboratories; two types of earmuff each measured at one laboratory; and a helmet measured at one laboratory. They used the analysis of variance to show the presence of a significant between-subject variance at all test frequencies. In their data within-subject variance accounted for between 34 per cent and 50 per cent of the total variance at all of the test frequencies.

The assumption implicit in the selection methods relates the variability of attenuation measurement solely to differences between subjects. However, in all of the studies that have been analysed there has been a significant within-subject variance.

It would be more appropriate, therefore, to state that the mean attenuation minus one standard deviation would be exceeded on approximately 84 percent of the occasions on which the hearing protectors are worn, rather than to state that attenuation exceeding this value is received by 84 percent of the wearers.

Correlation Between the Attenuation Distributions at Different Frequencies

The nth centiles of the attenuation distributions at each frequency are assumed to be composed of measurements made on the same subject on the same occasion. The application of the nth centile attenuation values for each octave mid-band frequency to a noise spectrum will then yield an estimate of the A-weighted sound level at the ears for the nth centile of a population of wearers (L_{An}). Therefore, from Equation 1-1:

$$L_{An} = 10 \log \sum_{x=63}^{8000} 10^{\frac{L_x - W_x - A_{xn}}{10}}$$

Equation 1-2

where A_{xn} is the lowest attenuation provided to the nth percentile at frequency x hertz.

To test this assumption, it is necessary to apply many individual attenuation spectra* separately to a noise spectrum. From each of the individual attenuation spectra can be obtained an estimate of the amount by which the A-weighted noise level from the noise spectrum would have been reduced, if the hearing protector had been worn in that noise on the occasion of the test.

If the assumption is correct, then the distribution of these reductions in A-weighted sound level should coincide with that predicted from:

$$R = 10 \log \sum_{x=63}^{8000} 10^{\frac{L_x - W_x}{10}} - 10 \log \sum_{x=63}^{8000} 10^{\frac{L_x - W_x - A_{xn}}{10}}$$

<u>Equation 1-3</u>

where n takes the values zero to one hundred and R is the reduction in A-weighted sound level provided by the hearing protector.

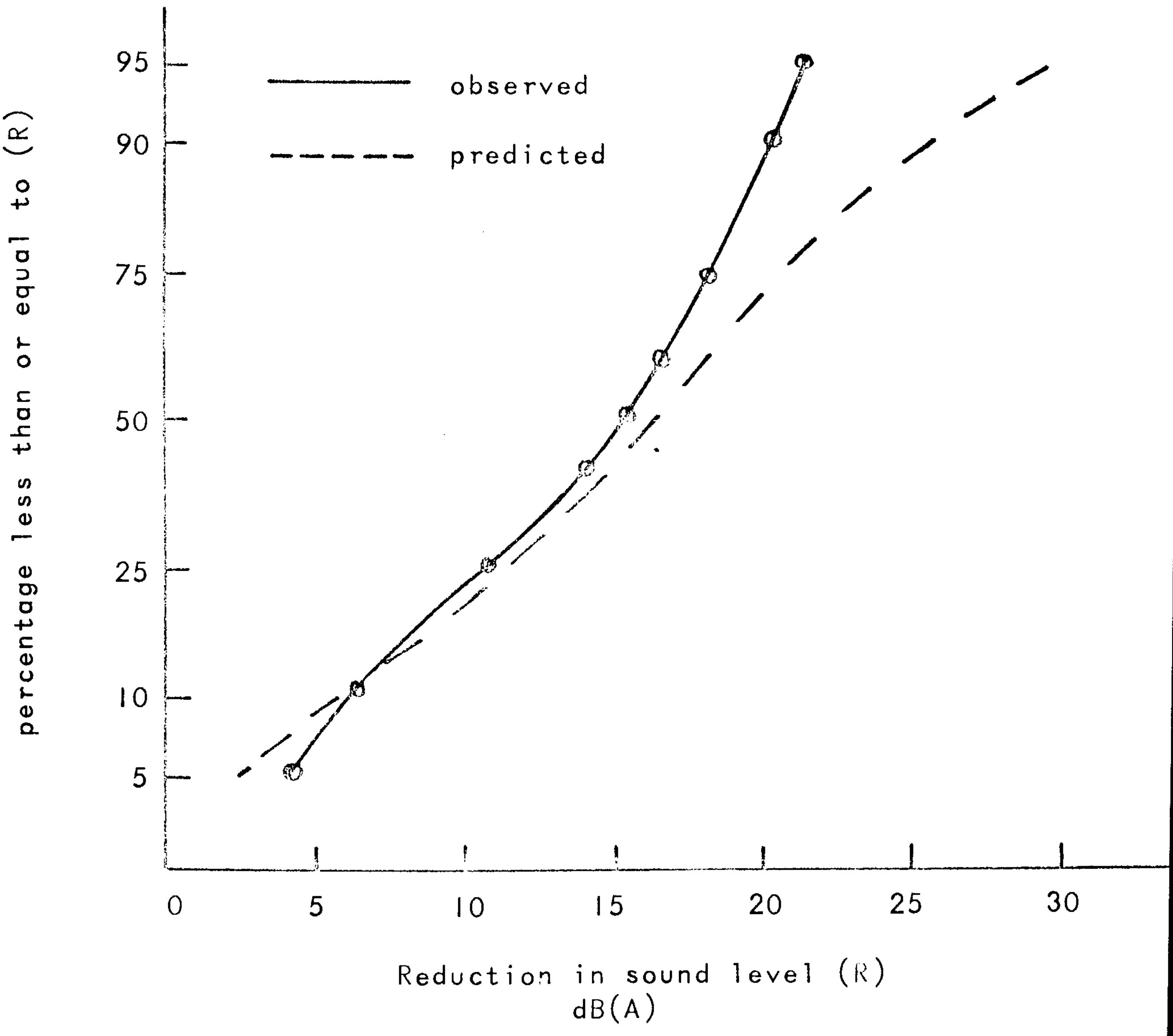
The sixty individual attenuation spectra obtained from the measurements on glass down earplugs (Appendix II) have been applied to a flat spectrum of noise. The resultant reductions in A-weighted sound level are displayed in the form of a cumulative distribution in Figure 1-13. Also shown in Figure 1-13 is the cumulative distribution of A-weighted reduction predicted by Equation 1-3 based on the assumption that the attenuation distributions at each frequency are directly

---

* the attenuation measured on one subject on one occasion at each of the test frequencies.

FIGURE I-13

Cumulative Distributions of the Reduction in A-Weighted Sound Level (R) Provided by Glass Down Earplugs in a Flat Noise Spectrum : Individual Attenuation Spectra Applied to the Noise Spectrum Compared with the Distribution Predicted from Equation 3



related.

The observed cumulative distribution differs significantly from that predicted by Equation I-3.
(Kolmogorov - Smirnov one-sample two-tailed test at significance level of $P = 0.05$.)
The distributions are seen to diverge by the greatest amount at the highest centiles. The very high A-weighted reductions predicted by Equation I-3 are not obtained in practice.

In Figure I-14 the cumulative distribution of overall attenuation obtained from the sixty individual attenuation spectra applied to a fast rising spectrum (8dB/octave) is compared with that predicted by Equation I-3. The two distributions diverge by the greatest amounts at the high percentiles and the distributions differ significantly.
(Kolmogorov - Smirnov one-sample two-tailed test at a significance level of $P = 0.05$.)

The cumulative distributions obtained with a fast falling spectrum (8dB/octave) are shown in Figure I-15. The two distributions do not differ significantly.
(Kolmogorov - Smirnov one-sample two-tailed test at a significance level of $P = 0.05$.)

Next it is necessary to examine whether the Equation I-3

FIGURE 1-14

Cumulative Distributions of the Reduction in A-Weighted Sound Level (R) Provided by Glass Down Earplugs in a Fast-rising Spectrum (8dB/octave): Individual Attenuation Spectra applied to the Noise Spectrum Compared with the Distribution Predicted from Equation 3

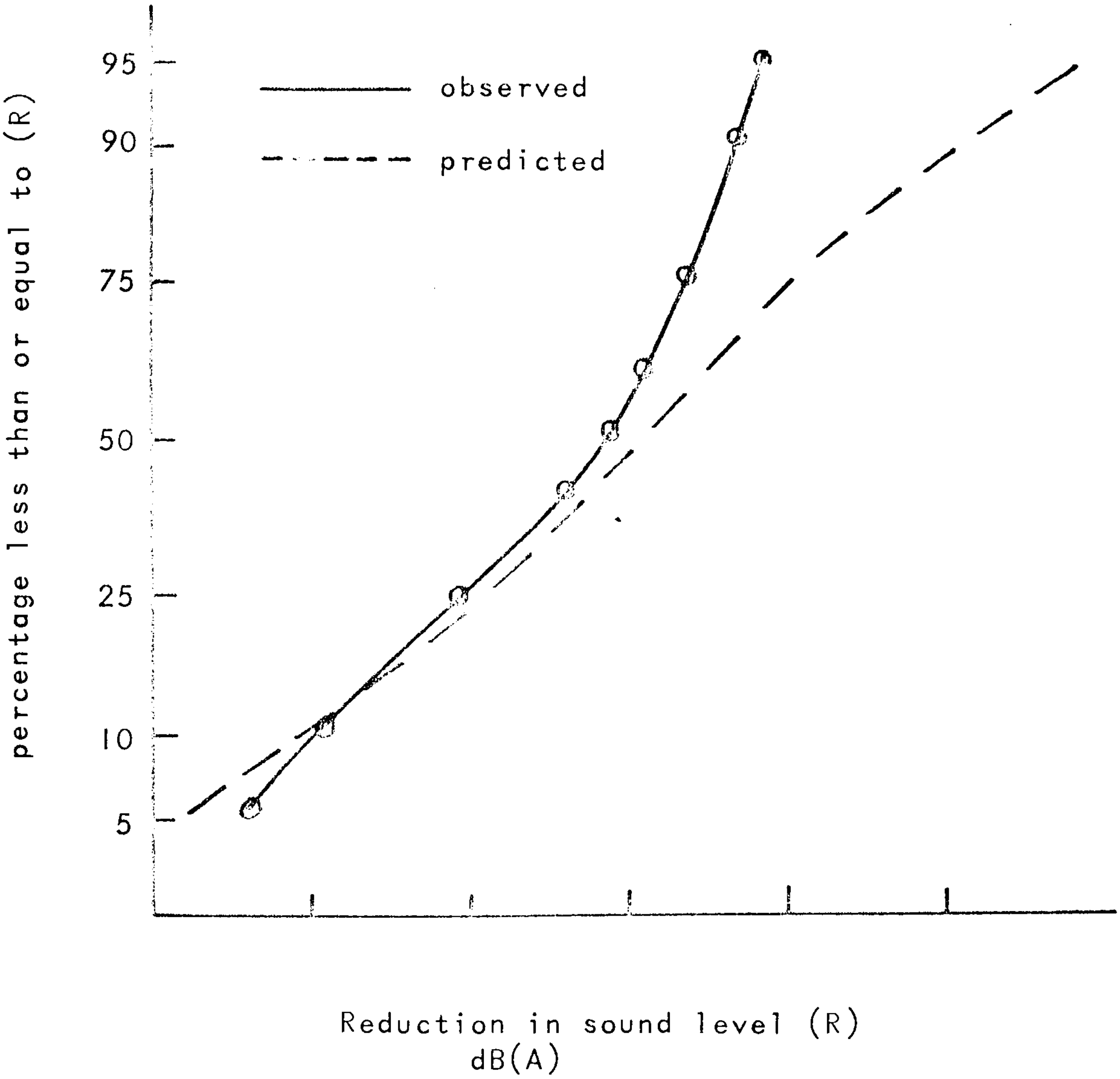
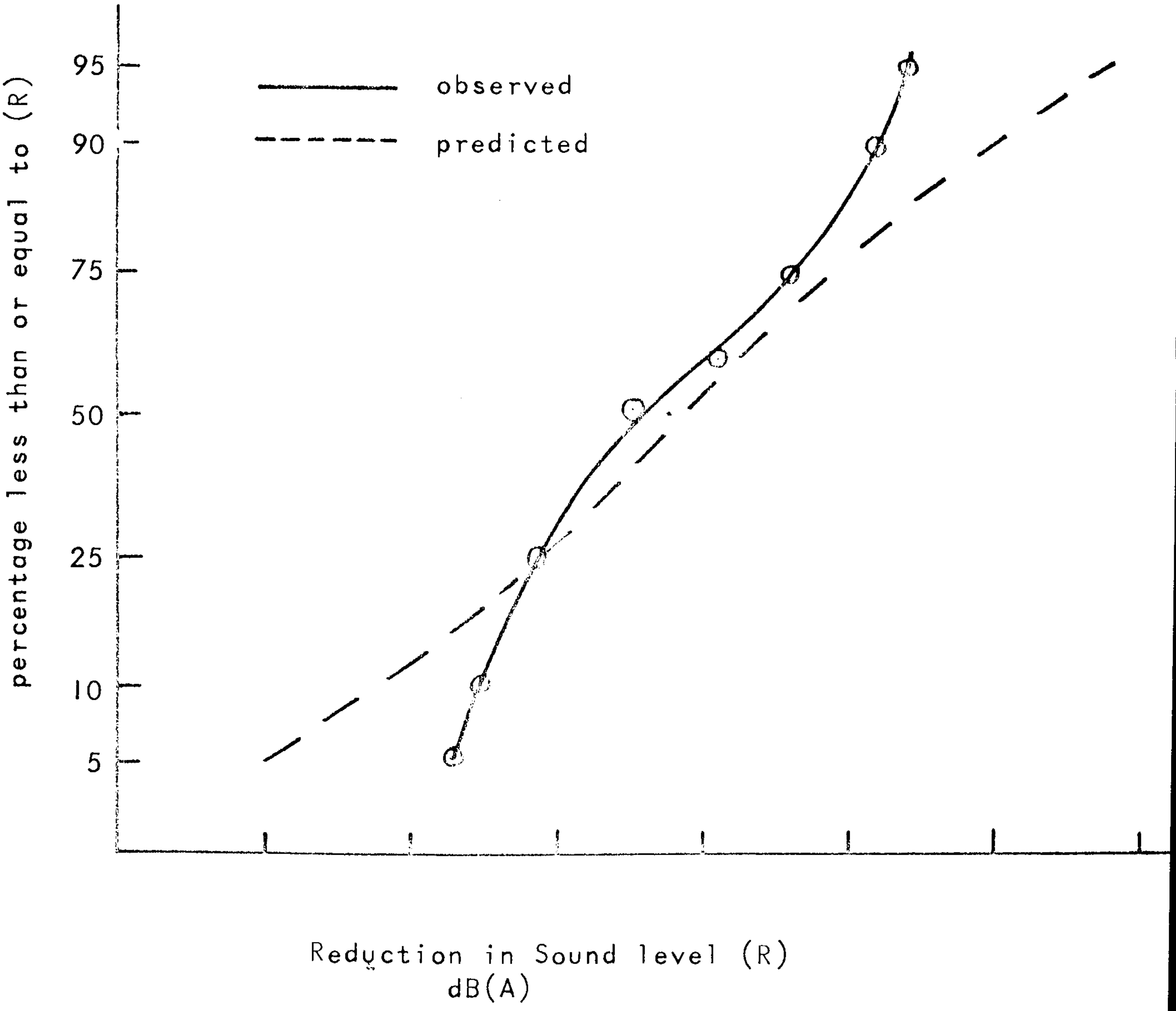


FIGURE I-15

Cumulative Distributions of the Reduction in A-Weighted Sound Level (R) Provided by Glass Down Earplugs in a fast-falling Spectrum (8dB/octave) : Individual Attenuation Spectra Applied to the Noise Spectrum Compared with the Distribution Predicted from Equation 3



and therefore the selection procedure describes accurately the percentages of wearers receiving small A-weighted reductions from the hearing protectors. The distribution of A-weighted reductions for the fast rising spectrum has been divided into a group containing the highest 30 reductions and a group containing the lowest 30 reductions.

These have been plotted as cumulative distributions in Figure 1-16, and are compared with the cumulative distributions predicted from Equation 1-3. As can be seen from Figure 1-16, the cumulative distributions for the 50 percent of wearers receiving the higher A-weighted reductions differ significantly.

(Kolmogorov - Smirnov one-sample two-tailed test at significance level P = 0.05.)

However, the distributions for the 50 percent of wearers receiving the lower reductions do not differ significantly.

(Kolmogorov-Smirnov one-sample two-tailed test at significance level P = 0.05.)

The A-weighted reductions obtained from analysis with a fast falling spectrum have also been divided into higher and lower 50 percent groups. These are shown in the form of cumulative distribution in Figure 1-17.

FIGURE 1-16

Cumulative Distributions of the Reduction in A-Weighted Sound Level (R) Provided by Glass Down Earplugs in a Fast-Rising Noise Spectrum (8dB/octave): Individual Attenuation Spectra Applied to the Noise Spectrum Compared with the Distribution Predicted from Equation 3

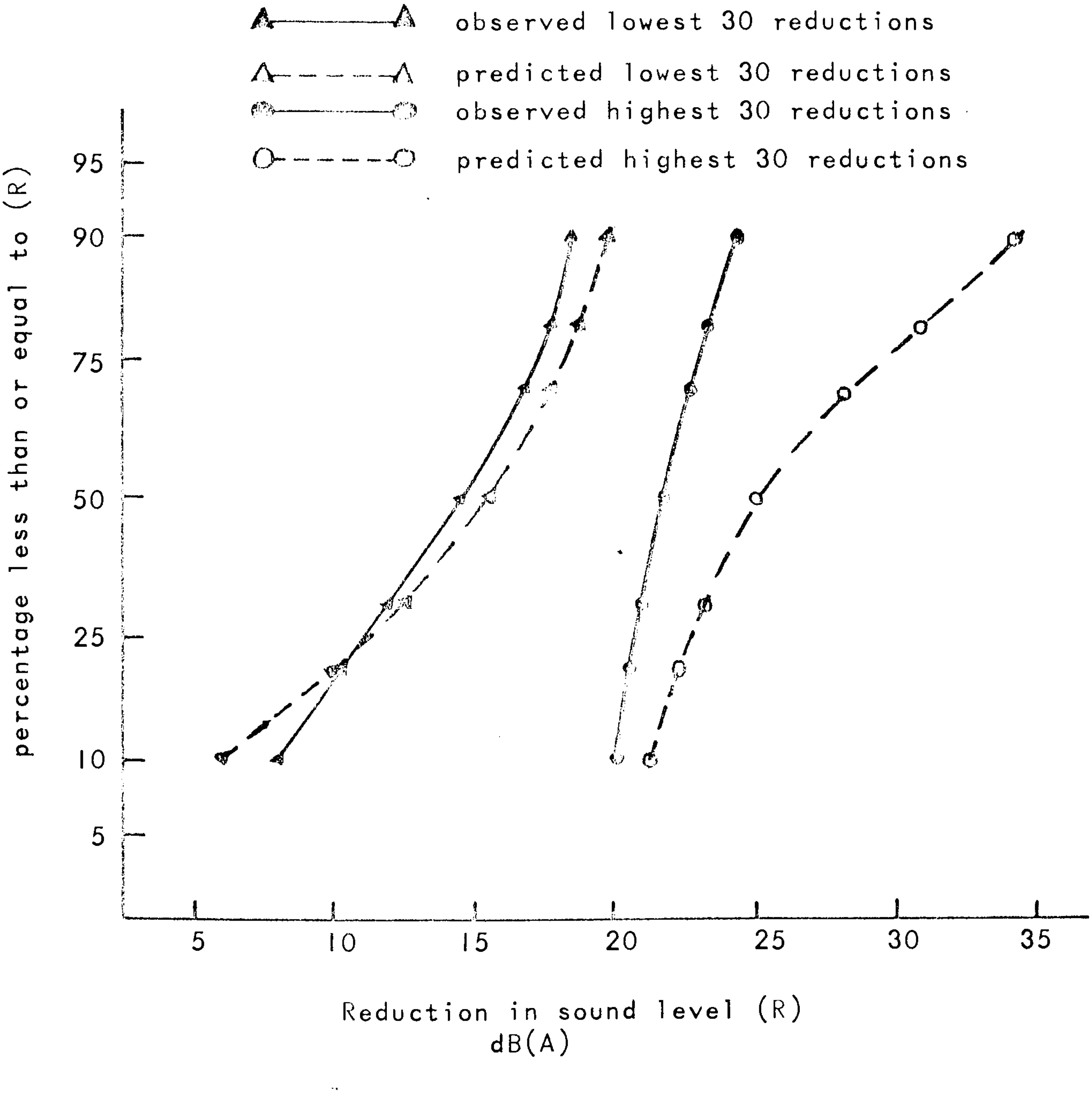
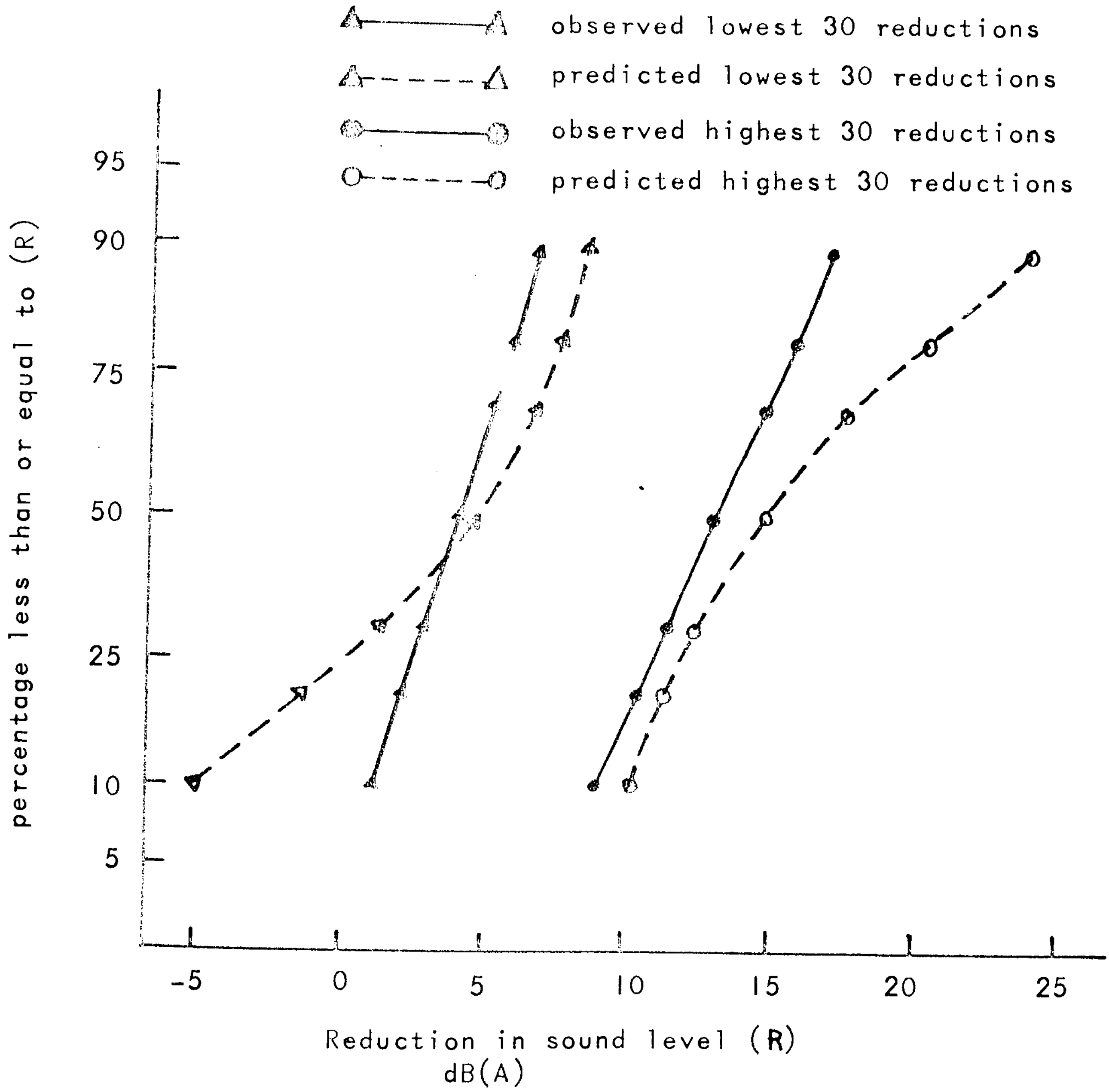


FIGURE I-17

Cumulative Distributions of the Reduction in A-Weighted Sound Level (R) Provided by Glass Down Earplugs in a Fast-Falling Noise Spectrum (8dB/octave) : Individual Attenuation Spectra Applied to the Noise Spectrum Compared with the Distribution Predicted from Equation 3



The distributions do not differ significantly from the cumulative distributions predicted by Equation 1-3 for either of the groups.
(Kolmogorov - Smirnov one sample two-tailed test at significance level P = 0.05.)

Similar analysis on raw data provided by Hanson and Blackstock (1958) on V51-R earplugs and by Martin (1973) on Peacekeeper moulded inserts has shown that the distributions of A-weighted reductions and the distributions predicted by Equation 1-3 do not differ significantly (0.05 significance level) for the lower 50 centiles, irrespective of whether the noise spectrum is flat, fast rising or fast falling. However, the predicted distributions do differ significantly for the upper 50 centiles when the noise spectrum is flat or fast rising.

It appears, therefore, that for those persons receiving high reductions of the flat or fast rising noise spectra the distribution does not follow the assumption of closely related attenuation distributions at all frequencies; the A-weighted reduction is limited by those octave bands which permit the passage of most A-weighted sound energy.

However, for persons receiving the low reductions in A-weighted sound level for any noise spectrum the assumption of closely related attenuation distributions is adequate.

The Effect of Within-Subject Variance on the Reduction in A-Weighted Sound Energy

If the protection (P) provided by a hearing protector for any one wearer is defined as the reduction in A-weighted equivalent-continuous sound level provided by the protector, expressed in decibels, then:

$$P = 10 \log \int_{f=0}^{\infty} \int_{t=0}^{T} I_f \, df \, dt \; - \; 10 \log \int_{f=0}^{\infty} \int_{t=0}^{T} I_f \times 10^{-A/10} \, df \, dt$$

Equation I-4

where I_f is the A-weighted sound intensity at frequency f and A is the attenuation provided by the hearing protector to sound of frequency f at time t during the period of noise exposure.

Since the functional relationship connecting A, f and t is not known, the protection cannot be calculated precisely.

However, if the reduction in A-weighted sound level (R) provided against a noise for one person on a number of occasions n, is known, then Equation I-4 can be approximated by the relationship

$$P = 10 \log I - 10 \log \left[I - \frac{1}{n} \sum_{1}^{n} 10^{\frac{I - R}{10}} \right]$$

Equation I-5

where I is the A-weighted sound intensity.

In the glass down experiment previously mentioned (Appendix II), the attenuation was measured on each of ten subjects on six occasions; six estimates of R can therefore be made for each subject in any noise. In Table I-7, the results of applying Equation I-5 to the individual attenuations for each subject are shown. They have been calculated for flat, fast rising and fast falling noise spectra and are compared with the mean reduction in sound level provided to each subject for each of the noises.

As can be seen from Table I-7, the time-weighted estimates of reduction in A-weighted sound energy are always less than that predicted from the mean of the individual reductions in sound level for each subject. The inclusion of the energy consideration applied to within-subject variance always results in less protection than would otherwise be expected.

The protection estimates from Table I-7 are displayed in Figures I-18, I-19 and I-20 as cumulative distributions. They are compared with the cumulative distributions predicted by the selection procedure (ie. by Equation I-3).

The inclusion of the energy consideration applied to within-subject variance has resulted in even greater divergence from the predicted distribution at high centiles. The difference between the distributions is significant for both

TABLE 1-7

A Comparison of the Mean Reduction in A-Weighted Sound Level ($\bar{R}$) Provided by Glass Down Earplugs for each Subject with the Calculated Reduction in Equivalent-Continuous Sound Level (P)

	Subject									
	1	2	3	4	5	6	7	8	9	10
FLAT SPECTRUM										
Mean reduction $\bar{R}$ dB(A)	15.1	8.6	13.6	10.5	17.8	12.9	15.2	18.3	17.4	15.5
Protection P dB(A)	13.8	6.7	10.8	8.1	17.0	11.8	14.3	15.9	15.7	12.7
Difference dB(A)	1.3	1.9	2.8	2.4	0.8	1.1	0.9	2.4	1.7	2.8
RISING SPECTRUM*										
Mean reduction $\bar{R}$ dB(A)	20.1	12.1	17.9	13.5	22.1	17.2	19.4	21.6	19.8	18.7
Protection P dB(A)	18.1	10.1	13.8	9.4	20.8	15.8	17.7	19.6	18.4	16.7
Difference dB(A)	2.0	2.0	3.9	4.1	1.3	1.4	1.7	2.0	1.4	2.0
FALLING SPECTRUM*										
Mean reduction R dB(A)	6.4	3.8	6.6	5.4	10.7	6.5	9.5	13.6	13.2	10.8
Protection P dB(A)	5.6	2.6	5.4	4.2	8.7	5.1	8.3	10.0	12.2	7.5
Difference dB(A)	0.8	1.2	1.2	1.2	2.0	1.4	1.2	3.6	1.0	3.3

* 8dB/octave

FIGURE 1-18

Cumulative Distributions of the Reduction in ECSL (Protection) Provided by Glass Down Earplugs Against a Flat Spectrum of Noise : Energy-Weighted Estimates Compared with Distribution Predicted from Equation 3

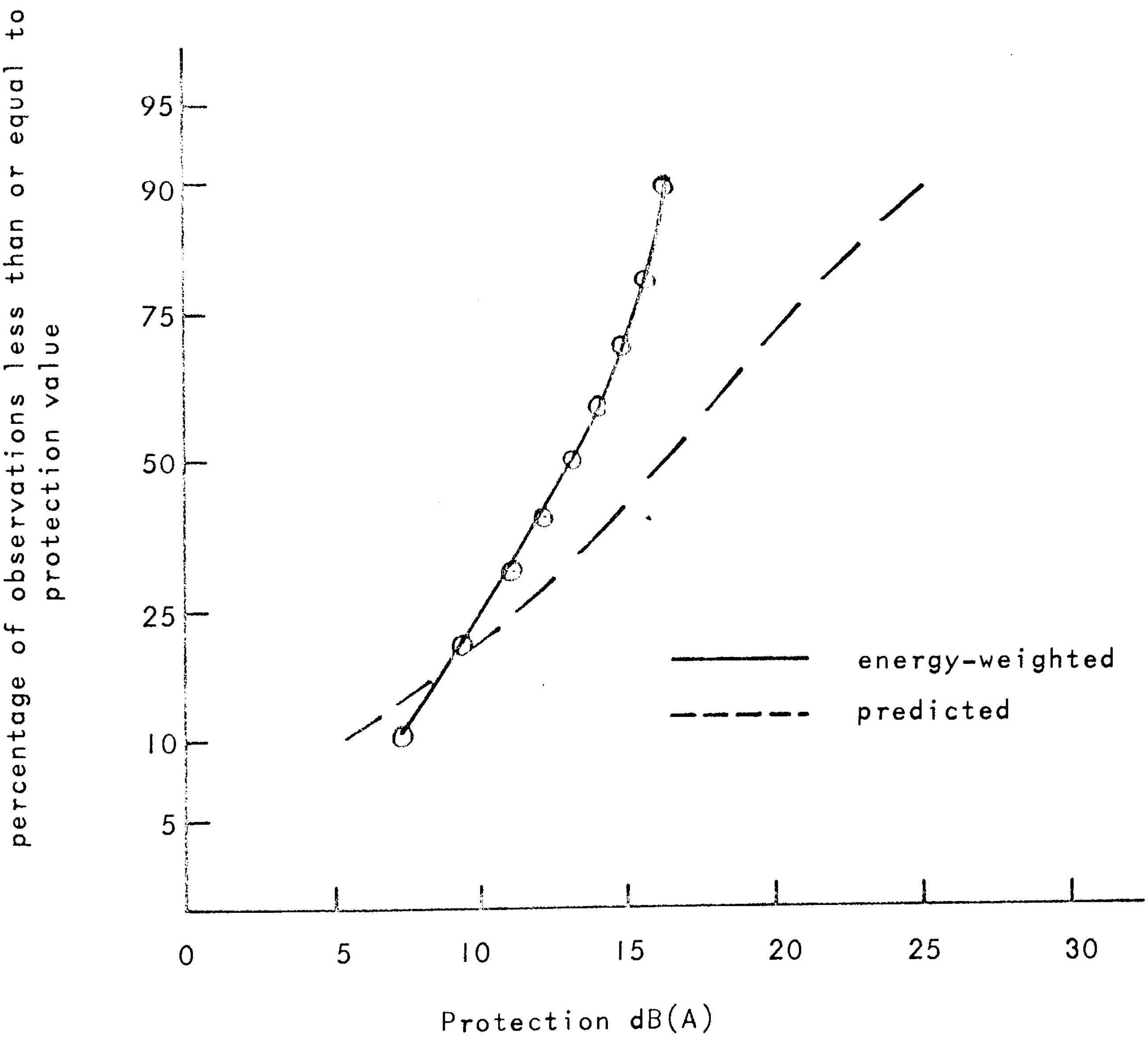


FIGURE 1-19

Cumulative Distributions of the Reduction in ECSL (Protection) Provided by Glass Down Earplugs Against a Fast-Rising Spectrum of Noise : Energy-Weighted Estimates compared with Distribution Predicted from Equation 3

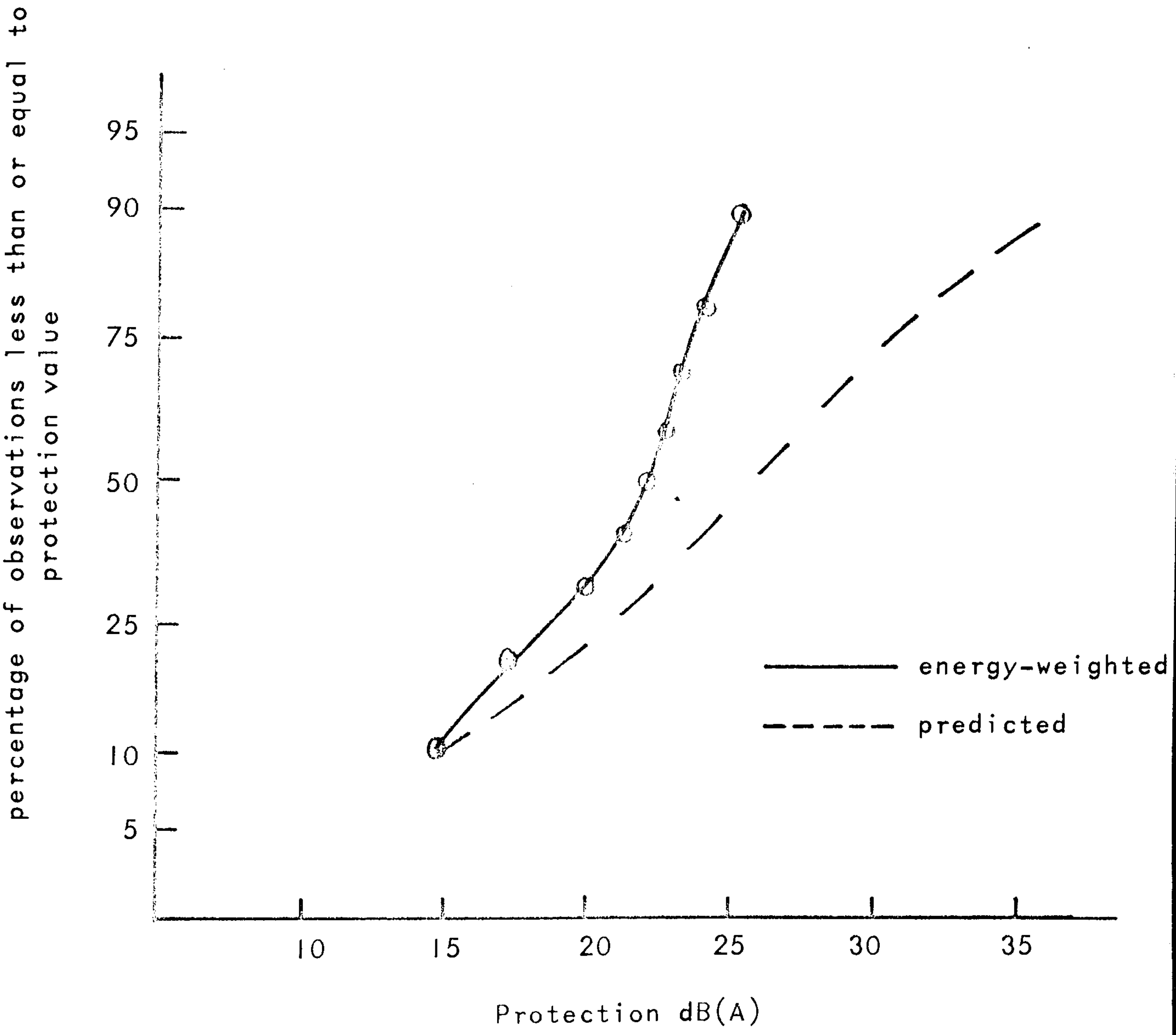
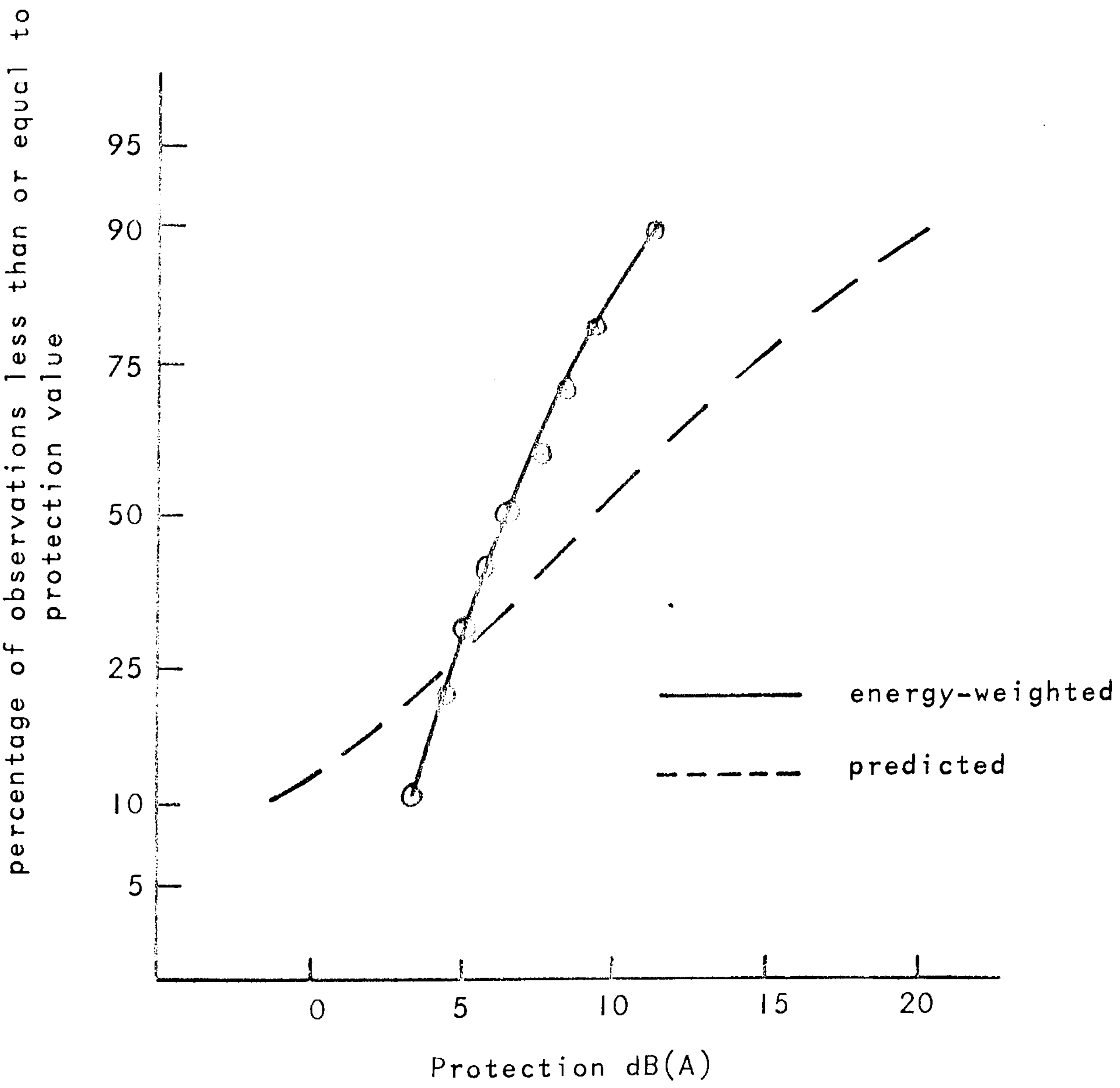


FIGURE I-20

Cumulative Distribution of the Reduction in ECSL (Protection) Provided by Glass Down Earplugs Against a Fast-Falling Spectrum of Noise : Energy-Weighted Estimates Compared with the Distribution Predicted from Equation 3



the flat and fast rising spectra but not for the fast falling spectrum.

(Kolmogorov - Smirnov one-sample two-tailed test at significance level P = 0.05.)

From Table I-7, the lowest five protection values obtained for the fast rising spectrum have been plotted as a cumulative distribution in Figure I-21. This is compared with the predicted distribution. There is no significant difference between the distributions,

(Kolmogorov - Smirnov one-sample two-tailed test with significance level P = 0.05.)

but this is based on only five data points. However, when the distribution of the upper five protection values is compared with the predicted distribution (Figure I-21) even though there are only five data points, the difference is significant.

(Kolmogorov - Smirnov one-sample two-tailed test with significance level P = 0.05.)

Similarly, protection values for the fast falling spectra are displayed in Figure I-22. There is not a significant difference between the distribution of protection values and predicted distributions for the lowest five data points, but the distribution of the upper five data points does differ

FIGURE I-21

Cumulative Distributions of the Reduction in ECSL (Protection) Provided by Glass Down Earplugs Against a Fast-Rising Spectrum of Noise : Energy-Weighted Estimates Compared with Distributions Predicted from Equation 3

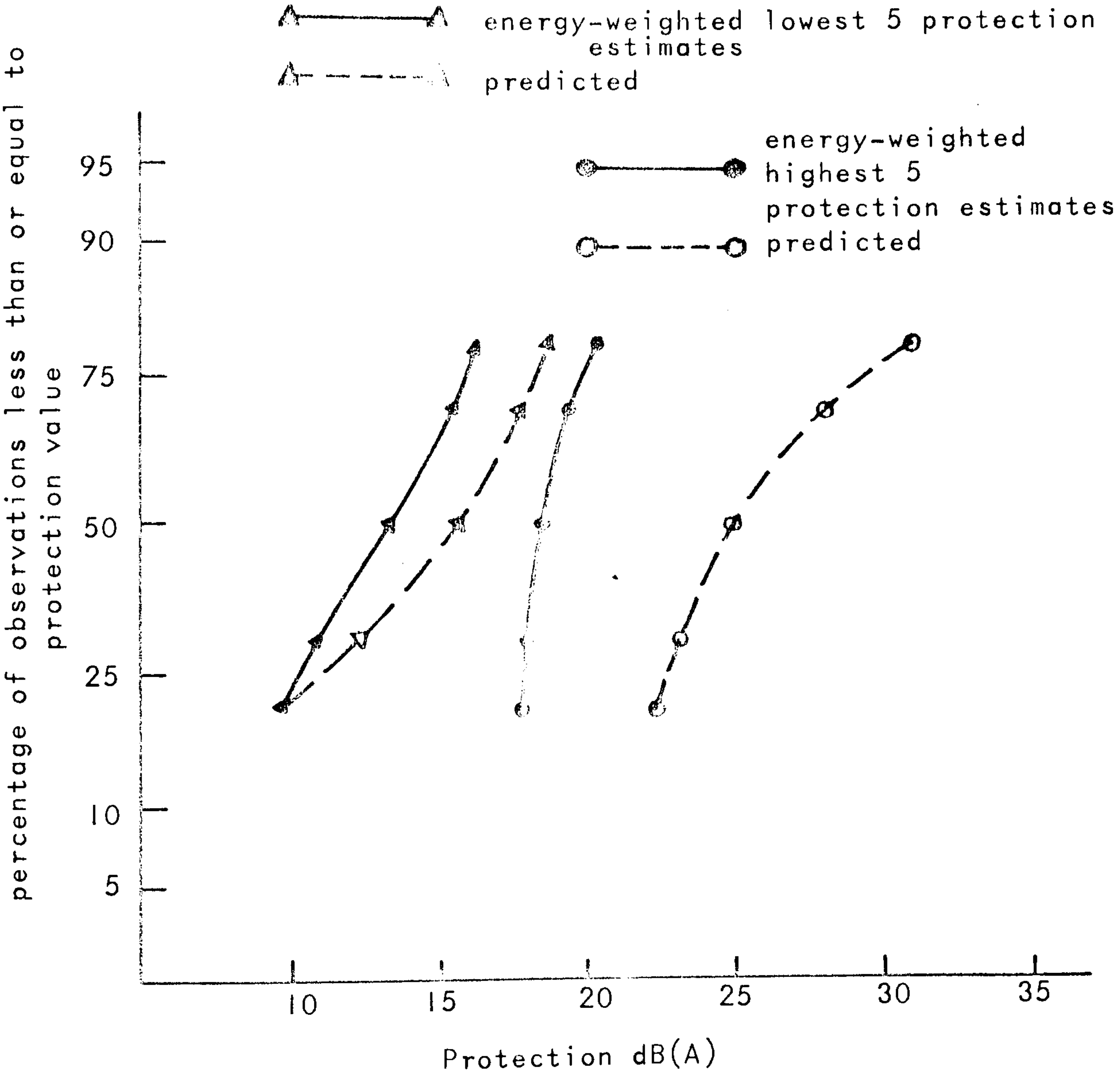
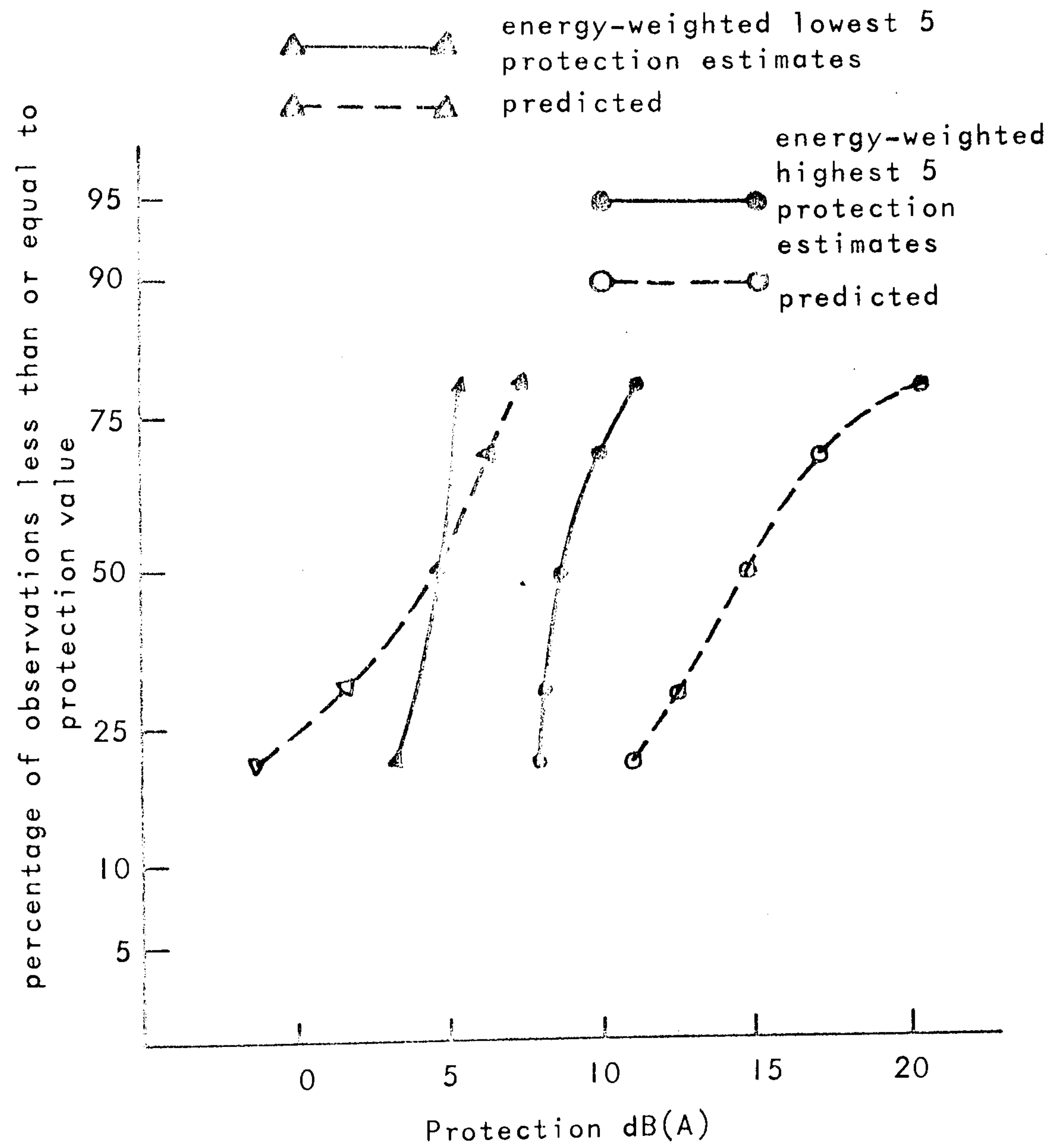


FIGURE 1-22

Cumulative Distributions of the Reduction in ECSL (Protection) Provided by Glass Down Earplugs Against a Fast-Falling Noise Spectrum : Energy-Weighted Estimates Compared with Distribution Predicted from Equation 3



significantly from the predicted distribution.

Analyses with the attenuation data provided by Hanson and Blackstock (1958) and Martin (1973) have failed to show a significant difference between the lowest 50 centiles of the distributions of protection and the predicted reduction in A-weighted sound level for the lowest 50 centiles.

The use of the selection procedure which neglects the within-subject variance does result in over-estimation of the amount by which hearing protectors reduce the noise energy for the higher centiles. However, the selection procedure does not significantly over-estimate the reduction afforded to the lower centiles and it is unlikely that the selection procedures would be applied on the basis of protecting less than 50 percent of the wearers.

Contributions to the A-Weighted Sound Level at the Occluded Ears from Frequencies Above 11313Hz and below 44Hz

I have not tested this assumption. For most industrial noise spectra contributions to the A-weighted sound level at the occluded ears from frequencies outside the range 44Hz to 11.3kHz should be negligible. This is partly because industrial noise spectra rarely have high levels in the 31.5Hz and the 16kHz octave bands and partly because the A-weighting corrections are large for these bands.

For the contribution from the 31.5Hz octave band or the 16kHz octave band to add one decibel to the A-weighted level beneath the hearing protectors, the following conditions would be necessary:

$$L_{31.5} - 39.4 \geqslant 10 \log \sum_{x=63}^{8000} 10^{\frac{L_x - W_x - A_x}{10}}$$

Equation 1-6

OR

$$L_{16000} - 6.6 \geqslant 10 \log \sum_{x=63}^{8000} 10^{\frac{L_x - W_x - A_x}{10}}$$

Equation 1-7

Summary

The early criteria for limiting noise exposure recommended limits for individual octave bands. The procedures devised for selecting hearing protectors for protection against particular noises were therefore applied to individual octave bands. Because the selection procedures were applied to individual octave bands, very few assumptions had to be made.

The introduction of standards based on cumulative

A-weighted sound energy resulted in the formulation of procedures for selecting hearing protectors based on A-weighted sound levels. Because hearing protectors do not attenuate all frequencies by the same amount the selection procedures use octave band analyses and octave mid-band attenuation data to estimate the A-weighted sound levels at the ears when hearing protectors are worn. Estimates of the occluded octave band levels have to be combined to estimate the A-weighted sound level at the occluded ears.

Many more assumptions have to be made with these selection procedures than with the previous procedures based on octave band noise limits.

Hearing protector selection procedures use one attenuation estimate per octave band. If third octaves of random noise have been used in the attenuation test, the attenuation will not have been estimated over two-thirds of each octave.

Results from objective attenuation tests in which the attenuation had been measured in all third-octaves were applied to flat and falling third-octave band spectra. The reductions in A-weighted sound level calculated by this method were within 0.5dB(A) of the reductions calculated by using only one-third octave attenuation measurement applied to each octave band.

The individual A-weighted octave bands have to be combined in order to provide an estimate of the overall A-weighted sound level at the ear. Because the selection procedures attempt to estimate the minimum reduction in A-weighted sound level provided to a specified proportion of wearers, the assumption has to be made that attenuation distributions at each frequency are directly related (i.e. the subjects comprising the tail of the attenuation distribution at one frequency also comprise the tail of the distributions at all other frequencies).

Individual attenuation measurements have been applied to complete noise spectra to obtain estimates of the A-weighted reduction afforded by a hearing protector on each occasion. The distributions of the A-weighted reductions were compared with the distributions predicted by the selection procedures. The selection procedures were shown to significantly overestimate the reduction provided to the upper centiles, but they did not overestimate the reductions provided by the hearing protector for the lower centiles.

The overestimating of the A-weighted reductions for the upper centiles is consistent with the reality that the A-weighted level inside the hearing protector will be primarily set by the octave band which allows passage of the most sound energy - very high attenuations in other octave bands will not significantly affect the reduction provided by the hearing protector. A poor fit of the hearing protector to the ear may result in low attenuation at a number of frequencies and not with just one octave band - this may explain why the reduction provided to the lower centiles was not overestimated by the selection procedures.

Since the selection procedures always aim to protect greater than 75 percent of the wearers, the assumption of the closely related attenuation distributions may be valid.

I was not able to refute the assumption of normality of attenuation distributions even though the distributions of attenuation data that were analysed had vastly different variances and were drawn from measurements on both earplugs and earmuffs.

The assumption that there is negligible within-subject variance was shown to be incorrect. Most attenuation data for earmuffs and earplugs showed the presence of a significant within-subject variance. The claims of the selection procedures to protect a specified proportion of wearers was shown therefore not to be completely valid; this is because any one wearer might receive high attenuation on most occasions, but low attenuation on other occasions.

However, the assumption that the variance in the distributions is produced by differences between persons has greater consequence. The presence of significant within-subject variance implies that persons wearing hearing protectors are on some occasions exposed to much higher sound levels than on other occasions, even though the ambient noise level is unchanged. Since the noise exposure criteria based on A-weighted sound energy provide a trading relation between noise level and exposure duration, the within-subject variance will result in a lowering of the overall protection provided by the hearing protectors.

To examine this assumption more closely, individual measurements of attenuation were applied to noise spectra and the results for each subject measured on a number of separate occasions were combined to estimate the reduction in equivalent-continuous sound level provided by the hearing protector. Estimates for each subject were obtained for the protection afforded by the hearing protector over the total time that the hearing protector was worn.

It was shown that the energy-weighted protection estimates for the upper centiles were significantly less than the reductions predicted by the selection procedures. However, the energy-weighted protection estimates for the lower centiles were not significantly different from the reductions predicted by the selection procedures. This could be explained if those persons receiving low attenuation always receive low attenuation whenever they wear hearing protectors, perhaps because they are a poor fit. Those persons receiving high attenuation probably do not always receive very high attenuation and therefore the long-term reduction in A-weighted sound energy will be seriously degraded by the occasions on which lower A-weighted reductions are obtained.

The selection procedures based on A-weighted sound levels assume that contributions to the total energy received by the occluded ears from frequencies below 44Hz and above 11313Hz are insignificant. This assumption is unlikely to introduce many errors in practice.

The hearing protector selection procedures based on A-weighted sound levels can be used to estimate the reduction in A-weighted sound level provided by the protector, but it must be remembered that the procedures are based on many assumptions, many of which do not hold under all applications of the selection procedures.

However, all of the assumptions of the selection procedures have been tested within the framework of one overriding assumption that the hearing protector is worn for the whole of the exposure duration.

APPENDIX II

APPENDIX II

MEASUREMENT OF THE ATTENUATION PROVIDED BY GLASS DOWN EARPLUGS

A binaural free-field threshold technique was used to measure the attenuation provided by earplugs made from glass down. The measurements were made with pure-tones of frequencies 125Hz, 250Hz, 500Hz, 1000Hz, 2000Hz, 4000Hz and 8000Hz. An attempt was made to simulate the fitting procedure that would be used in practice: the subjects were given instruction in the method of fitting prior to the experiments but during the experiments the subject fitted the plugs without supervision. The experimental method was basically that outlined in the American Standard method for the measurement of real-ear attenuation of ear protectors at threshold (ASA z24.22, 1957) but the attenuation was measured six times on each of the ten subjects at each of the test frequencies.

Equipment and Anechoic Chamber

The listening sessions were conducted in an anechoic chamber; the ambient noise level inside the chamber satisfied the requirements of ASA z24.22 (Martin, 1970). The experiments were supervised from a separate control room.

An audiometer was used to generate pure-tone signals. The output of the audiometer was fed via a power amplifier into an electrostatic loudspeaker. A random noise generator could be switched in place of the audiometer to provide a background noise in which the fit of the earplugs could be adjusted; random noise of equal energy per octave was used.

An intercom system enabled experimenter and subject to converse when necessary. The pure-tone stimuli were presented in pulses. The equipment did not produce audible clicks and there was no noise audible from the amplifier-speaker system when the audiometer and random noise generator were switched off.

Subjects

The ten subjects used in the experiment were university staff between the ages of 20 and 30 years: eight were male and two were female. All subjects had previously taken part in other threshold hearing tests. Each subject had hearing levels within the range ±10dB of normal hearing (BS 2497, 1954) at test frequencies 125Hz to 4000Hz and within the range -10dB to +20dB of normal hearing at the 8000Hz test frequency.

Fitting

Eight of the subjects participated in the tests on three consecutive days; for two subjects there was an interval of three days between the second and third test sessions.

Before the first test session the subject was shown how to fold the glass down into the earplugs. The glass down had previously been cut into pieces 6 cms by 3 cms. A random noise of 75dB(A) was provided so that the subject could adjust the earplugs to give the maximum attenuation without unreasonable discomfort. The subject repeated the folding and fitting procedure until his performance was considered to be adequate by the experimenter. Throughout the remainder of the experiments there was no further supervision of fitting. On each occasion that the subject fitted the earplugs he was asked to adjust them in the random noise. The subject was then asked to raise and lower the jaw vigorously ten times as described in ASA z24.22. The subject was then asked not to touch the earplugs throughout the test; he was also asked to keep his mouth closed during the tests.

Test Sessions

At each test session the subject had one determination of threshold at each frequency with the ears open and two determinations at each frequency with the ears occluded by earplugs. The order of these three sets of determinations at the seven test frequencies was randomised. A Békésy technique was used for the threshold determinations; the subject was asked to keep a button pressed down whilst the tone was audible and to release the button as soon as the tone was inaudible. The threshold determinations were always made in order of ascending frequency; the average of at least six threshold crossings was taken at each test frequency. A practice trial at 1000Hz was given before each set of determinations at the seven test frequencies.

For the occluded threshold tests new earplugs were folded and inserted before each set of determinations at the seven test frequencies.

Each test session consisted of three sets of determinations at the seven test frequencies; this took approximately 30 minutes.

Results

The attenuation provided by the glass down earplugs was taken as the difference between the occluded threshold and the open-ear threshold measured during the same session. The attenuation data from the six measurements made at each test frequency on each of the ten subjects are shown in Table II-I The mean and standard deviations of the data are also shown in Table II-I.

Discussion

The aim of the experiment was to measure the attenuation provided by glass down earplugs as fitted by the subjects. Subjects experienced considerable difficulty in forming

TABLE II-1

Attenuation Provided by Glass Down Earplugs: Six Measurements on each of Ten Subjects

Subject	Trial	Test frequency in hertz						
		125	250	500	1000	2000	4000	8000
1	1	-5	5	10	15	17	38	35
	2	10	8	13	16	38	38	28
	3	0	11	13	17	27	38	20
	4	-5	0	5	5	20	30	23
	5	5	7	10	13	40	30	33
	6	0	5	10	20	27	44	40
2	1	0	-5	0	18	13	10	0
	2	10	12	14	16	28	28	29
	3	-4	0	-4	5	13	25	20
	4	-3	3	0	18	20	22	0
	5	0	3	7	7	20	23	29
	6	2	0	-4	-4	8	25	20
3	1	9	8	13	20	30	33	28
	2	5	15	15	18	30	28	40
	3	0	5	10	14	20	23	15
	4	6	7	5	18	28	48	32
	5	-5	7	3	0	19	17	35
	6	0	5	4	5	18	18	15
4	1	-10	-10	0	12	-4	34	42
	2	10	2	5	13	33	26	13
	3	7	16	19	16	23	28	14
	4	-10	-5	8	16	10	33	30
	5	10	9	0	0	33	29	11
	6	3	8	5	18	20	26	20
5	1	19	10	12	21	32	24	17
	2	0	14	23	17	28	31	26
	3	15	13	17	27	40	34	20
	4	16	10	15	24	27	28	12
	5	0	5	16	10	25	18	23
	6	3	6	12	12	35	26	23

cont'd

TABLE II-I (cont'd)

Attenuation Provided by Glass Down Earplugs: Six Measurements on each of Ten Subjects

Subject	Trial	Test frequency in hertz						
		125	250	500	1000	2000	4000	8000
6	1	-4	5	5	10	19	28	30
	2	2	-2	4	8	24	19	25
	3	4	2	11	20	33	23	20
	4	0	-2	5	5	15	20	30
	5	15	18	15	15	19	27	23
	6	4	4	8	14	33	33	15
7	1	0	6	10	23	34	26	25
	2	9	8	10	5	25	20	30
	3	13	6	19	23	26	30	12
	4	0	8	12	15	20	30	40
	5	6	23	18	14	35	25	32
	6	20	13	10	23	33	27	5
8	1	22	24	23	34	43	32	30
	2	10	7	13	10	30	28	22
	3	10	9	13	17	23	35	10
	4	15	19	12	11	28	27	25
	5	0	4	6	12	25	20	20
	6	17	12	20	20	23	32	20
9	1	13	13	10	18	27	14	25
	2	18	20	16	20	36	22	24
	3	5	10	12	18	30	25	33
	4	13	18	15	23	27	18	23
	5	23	15	8	11	24	18	5
	6	5	15	15	14	27	25	27
10	1	6	-5	5	8	22	34	20
	2	15	10	15	13	31	45	38
	3	18	13	17	17	22	28	23
	4	6	-3	0	8	12	28	20
	5	15	13	17	13	28	42	30
	6	11	11	13	17	22	31	29
Mean Attenuation dB		6.3	8.1	10.2	14.4	25.2	27.8	22.7
Standard Deviation dB		7.9	7.3	6.3	6.8	8.5	7.3	9.4

earplugs on the basis of the instructions provided by the manufacturers. It was necessary, therefore, for the subjects to see earplugs being formed and inserted before they tried to fit them. Probably more time was taken to ensure that the subject could form and insert the earplugs than would be given in practice. However, in practice the wearers would probably have greater experience of folding and inserting the earplugs because they would be doing it every day.

APPENDIX III

APPENDIX III

COMPUTER MODEL FOR ESTIMATING THE RESIDUAL RISK OF OCCUPATIONAL DEAFNESS FOR HEARING PROTECTOR USERS

Hearing protectors are used to combat the risk of occupational deafness for populations exposed to hazardous noise. However, the use of hearing protectors may not completely eliminate the risk of occupational deafness for the users. A computer model has been developed to estimate the residual risk of occupational deafness for users of any particular type of hearing protector in any individual noise spectrum. The estimates of residual risk are based on a hearing level criterion of 25dBHL$_{\overline{0.512}}$*.

The computer model can be used to compare the reductions in risk afforded by high and low attenuation hearing protectors. The computer model can also be used to estimate the effect which protectors not being worn for part of the duration of noise exposure is likely to have on the residual risk.

The Computer Model

The residual risk of exceeding a hearing level criterion of 25dBHL$_{\overline{0.512}}$ is computed from the following data:

Noise exposure: Equivalent-continuous octave band sound levels** for the octave bands with mid-band frequencies, 63Hz, 125Hz, 250Hz, 500Hz, 1000Hz, 2000Hz, 4000Hz and 8000Hz.

---

* The risk of exceeding a mean hearing level of 25 decibels for the average of 500Hz, 1000Hz and 2000Hz.

** The octave band sound level which in eight hours would deliver the same amount of unweighted sound energy within the octave band as the actual exposure over the actual working day.

Hearing protector: Attenuation data in the form of estimates of mean and standard deviation for each octave band.

The model is outlinedin Figure III-I. The risk for each centile of the population of hearing protector users is calculated from the noise exposure and hearing protector data and summed for all centiles to calculate the risk for the population.

The centile estimates of attenuation for each of the eight octave mid-band frequencies are calculated on the assumption that attenuation is normally distributed at all frequencies*. The equivalent continuous sound level (ECSL) for the p th centile of hearing protector users is calculated from Equation 9 from Chapter 2,

$$\mathrm{Leqp} = 10 \log \left[10^{\left(\frac{\mathrm{leq}}{10} - \log\frac{100}{100-V}\right)} + 10^{\left(\log \sum_{x} 10^{\frac{Lx-Wx-Axp}{10}} - \log \frac{100}{V}\right)} \right]$$

Equation III-1

where Leqp is the ECSL for the pth centile of the population of wearers; Lx is the equivalent continuous octave band sound level for the octave band centred at x hertz; Wx is the A-weighting correction at x hertz; and Axp is the attenuation provided by the hearing protector to sound of the corresponding octave band for the pth centile of wearers. V is the percentage of the exposure duration for which the hearing protectors are worn.

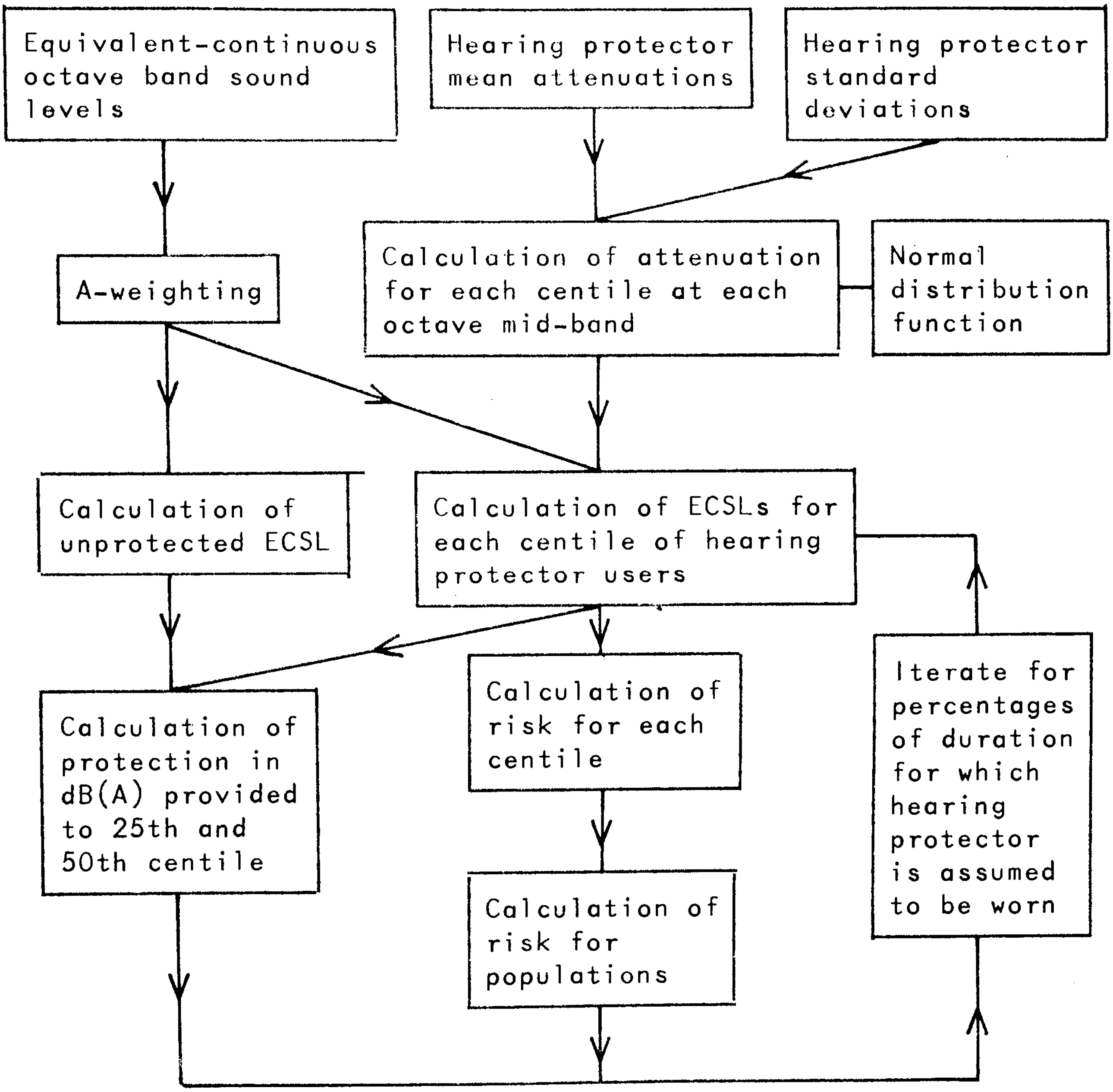
---

* The mean and standard deviation of attenuation of

cont'd

FIGURE III-1

FLOW DIAGRAM FOR THE COMPUTER MODEL



data are used as population estimates; because the data are usually the results of at least thirty determinations; best-estimate population corrections have not been included in the model.

The risk of exceeding $25\text{dBHL}_{\overline{0.512}}$ for each centile of hearing protector users is calculated from a cubic approximation to the risk curve shown graphically in Figure I, Chapter 2.

$$Fp=2910.1 - 92.128Leqp + 0.948Leqp^{2} - 0.003Leqp^{3}$$

Equation III-2

where Fp is the risk of exceeding $25\text{dBHL}_{\overline{0.512}}$ for the pth centile of hearing protector users who have been exposed for forty-nine years, from the age of sixteen years, to an ECSL of Leqp for five days per week and forty-eight weeks per year.

The boundary conditions for Equation III-2 are that Fp = 4 percent when Leqp = 80dB(A) and Fp = 89 percent when Leqp = 120dB(A). The risk derived from Equation III-2 is accurate to within one percent throughout the range 80dB(A) to 120dB(A).

The residual risk (R) for the population of hearing protector users is calculated from

$$R = \sum_{p=1}^{100} Fp$$

Equation III-3

An example of the program based on the model is shown in Figure III-2. An example of the output from the program

FIGURE III-2

Computer Model for Estimating the Residual Risk of Exceeding a Hearing Level Criterion for a Population of Wearers of Hearing Protectors - Programme and Sample Output using the Criterion of 25dB $HL_{\overline{0.512}}$ for a Working Lifetime of 49 Years

```
'BEGIN'
'INTEGER'  I,J,K,L,N,M,IN;
'ARRAY'  WC,WA,AWT,CWT(1:8),LATEN(1:8, 1:100),OCCLEV,RESL,
         RESR, Z(1:100);
'REAL' OLDBC,OLDBA,SPAI, SIGARR,SRESL,SOCCLEV,TERM,T2,LN10;
'REAL' 'PROCEDURE' F(X);
'COMMENT' CUBIC APPROXIMATION TO ROBINSON 25DBHL RISK
          MINIMUM IS4 MAXIMUM IS98;
'VALUE' X; 'REAL' X;
'BEGIN'
'REAL'DUMMY;
DUMMY:=
2910.1-92.128*X+0.94806*X 2-0.0031303*X 3;
F:='IF' DUMMY 4'THEN'4'THEN'ELSE' 'IF'DUMMY 98 'THEN'98
      'ELSE' DUMMY;
'END'
'PROCEDURE TEST';
'COMMENT SETS UP TABLES OF WEIGHTS AND REVERSE Z TABLE
FIRST SETS UP Z DISTRIBUTION FOR UPPER HALF OF DIST AT 1
PCT. POINTS, THEN 100p SETS UP LOWER HALF OF DIST IN Z(1)
TO Z(50),UPPER HALF IN Z(51) TO Z(100) AT 1 PCTILES;
'BEGIN'
CWT(7):=CWT(1):=1; CWT(2):=CWT(3):=CWT(4):=CWT(5):=CWT(6):=0;
CWT(8):=3;
AWT(1):=26;AWT(2);+16;AWT(3):=9;AWT(4):=3;AWT(5):=0;
AWT(6):=AWT(7):=-1; AWT(8):=1;
Z(51):=0.0;
Z(52):=.0251; Z(53):=.0502; Z(54):=.0753; Z(55):=.1004;
Z(56):=.1257; Z(57):=.1510; Z(58):=.1764; Z(59):=.2019;
Z(60):=.2275; Z(61):=.2533; Z(62):=.2793; Z(63):=.3055;
Z(64):=.3319; Z(65):=.3585; Z(66):=.3853; Z(67):=.4125;
Z(68):=.4399; Z(69):=.4677; Z(70):=.4959; Z(71):=.5244;
Z(72):=.5534; Z(73):=.5828; Z(74):=.6128; Z(75):=.6433;
Z(76):=.6745; Z(77):=.7063; Z(78):=.7388; Z(79):=7722;
Z(80):=.8064; Z(81):=.8416; Z(82):=.8779; Z(83):=.9154;
Z(84):=.9542; Z(85):=.9945; Z(86):=1.036; Z(87):=1.080;
Z(88):=1.126; Z(89):=1.175; Z(90):=1.227; Z(91):=1.282
Z(92):=1.341; Z(93):=1.405; Z(94):=1.476; Z(95):=1.555;
Z(96):=1.645; Z(97):=1.751; Z(98):=1.881; Z(99):=2.054;
Z(100):=2.326;
```

Computer Model (cont'd)

```
K:=50
'FOR' I:=52 'STEP' 1 'UNTIL' 100 'DO' 'BEGIN'
Z(K):= -Z(1); K:=K-1;
'END'
Z(1):= -6;
LN10:=LN(10);
'END'
N:=1; M:=72;
'BEGIN'
'ARRAY' P(1:N,1:9),ATT,SDS(1:M,1:9);
TSET;
 'FOR' I:=1 'STEP' 1 'UNTIL' N 'DO'
'FOR' J:=1 'STEP' 1'UNTIL' 9 'DO'
P(I,J):=88;
'FOR' I:=1 'STEP' 1 'UNTIL' 36 'DO'
'BEGIN'
'FOR J:=1 'STEP' 1 'UNTIL' 9 'DO'
ATT(I,J):=36.0-1;
'FOR' J:=1 'STEP' 1 'UNTIL' 9 'DO'
SDS(I,J):=5.0;
'END'
'FOR' I:=37 'STEP' 1 'UNTIL' 72 'DO'
'BEGIN'
'FOR' J:=1 'STEP' 1 'UNTIL' 9 'DO'
ATT(I,J):=72-I;
'FOR' J:=1 'STEP' 1 'UNTIL' 9 'DO'
SDS(I,J):=10.0;
'END'
'FOR' K:=1'STEP' 1 'UNTIL' N 'DO'
'FOR' I:=1 'STEP' 1 'UNTIL' M 'DO'
'BEGIN'
'FOR' I:=1 'STEP' 1 'UNTIL' 8 'DO'
'BEGIN'
WC(I):=P(K,I)-CWT(I);
WA(I):=P(K,I)-AWT(I);
'END'
'FOR' I:=1 'STEP' 1 'UNTIL' 8 'DO'
'FOR' J:=1 'STEP' 1 'UNTIL' 100 'DO'
'BEGIN'
LATEN(I,J):=Z(J)*SDS(L,I)+ATT(L,I);
'IF' LATEN(I,J)  -10.0 'THEN' LATEN(I,J):=-10.0;
'END'
SPA1:=SPA2:=0
'FOR' I:= 1 'STEP' 1 'UNTIL' 8 'DO'
```

cont'd

Computer Model (cont'd)

```
'BEGIN'
SPA1:=SPA1+10.0 (WC(I)/10.0);
SPA2:=SPA2+10.0 (WA(I)/10.0);
'END'
 OLDBC:=10*LN(SPA1)/LN10;
OLDBA:=10*LN(SPA2)/LN10;
SPA1:=SPA2:=0;
'FOR' I:=1 'STEP' 1 'UNTIL' 8 'DO'
'FOR' J:= 1 'STEP' 1 'UNTIL' 100 'DO'
LATEN(I,J):=WA(I)-Laten(I,J);
'FOR' I:=1 'STEP' 1 'UNTIL' 100 'DO'
'BEGIN'
'FOR' J:=1 'STEP' 1 'UNTIL' 8 'DO'
SPA1:=SPA1+10.0 (LATEN(J,I)/10.0);
OCCLEV(I):=10.0*LN(SPA1)/LN10;
SPA1:=0;
'END'
'FOR' I:=1 'STEP' 1 'UNTIL' 100 'DO'
SPA1:=SPA1+10.0 (OCCLEV(I)/10.0);
SRESL:=10.0*LN(SPA1)/LN10;
SOCCLEV:=SRESL-20.0;
WRITETEXT('(''('P')'P.%INDEX')')PRINT(P(K.9),8,0);
WRITETEXT('(''('C')'A.%INDEX');PRINT(ATT(L.9),8,0);
WRITETEXT('(''('C')'OCT.%BAND%CENTRE'(C')'FREQ.%HZ.
'('8S')'62.5 '('3S') ' 125 '('5S') ' 250 '(6S') ' 500
'('3S') ' 1000 '('5S') ' 2000 '('3S')' 4000 '('6S')'
8000 '('C')'OCT.%BAND%S. '('C')'LEVELS '('9S')'')');
'FOR' I:=1 'STEP' 1 'UNTIL' 8 'DO'
PRINT(P(K.I),3,1);
NEWLINE(1);
WRITETEXT ('('MEDIAN%ATTEN.'('2S')'')');
'FOR' I:=1 'STEP' 1 'UNTIL' 8 'DO'
PRINT(ATT(L.I),3,1,);
WRITETEXT('(''('C')'STANDARD%DEVS.%')');
 'FOR' I:= 1 'STEP' 1 'UNTIL' 8 'DO'
PRINT(SDS(L.I),3,1);
WRITEXT('(''('C')'OVERALL%LEVEL%DB(A)%=')');
PRINT(OLDBA,4,1);
WRITETEXT('(''('C')'OVERALL%LEVEL%DIFF%DB=')');
PRINT(OLDBC-OLDBA,4.1);
WRITETEXT('(''('2C')'LOWER%QUARTILE%PROTECTION%DB(A)=')');
); PRINT(OLDBA-OCCLEV(26),4,1);
 WRITETEXT('(''('3C' 10S')'PROTN%LEVEL%DB(A)%%%PCT%TOTAL
%RFSID%RISK'('C')'PCT%TIME   '('C')'WORN'('10S')'
```

cont'd

Computer Model (cont'd)

```
LQ%%%%%  MED '('7S')'  PEOPLE '('5S')'TIME'('C')'
')');
'FOR' SPA1:=100.0,99.5,99.0, 97.0,95.0,09.0,75.0,50.0 'DO'
'BEGIN'
PRINT(SPA1,2,00); SPACE (4);
'IF' SPA1 = 100 'THEN' TERM := 150 'ELSE'
TERM=10*1N(100.0/(100-SPA1))/LN10;
'IF' SPA1 = 0 'THEN' T2:= 150 'ELSE';
T2:=10*LN(100.0/SPA1)/LN10;
'FOR' I:= 1 'STEP' 1 'UNTIL' 100 'DO'
RESL(I):=10*LN(10.0 ((OLDBA-TERM)/10)+
         10.0 ((OCCLEV(I)-T2)/10))/LN10;
PRINT(OLDBA-RESL(26),3,1);
PRINT(OLDBA-RESL(51),3,1);
SPA2:=0;
'FOR' I:=1 'STEP' 1 'UNTIL' 100 'DO'
'BEGIN'
RESL(I):='IF' RESL(I) 'LE' 80
'THEN' 80 'ELSE' 'IF' RESL(I) 'GE' 120
'THEN' 120 'ELSE' RESL(I);
SPA2:=SPA2+F(RESL(I));
'END'
SPACE (5);
PRINT(SPA2/100,3,2);
NEWLINE (1);
'END' PAPERTHROW;
NEWLINE (1);
'END'
```

SAMPLE OUTPUT

```
OCT. BAND CENTRE
FREQ. HZ          62.5    125      250 500   1000 2000 4000 8000
OCT. BAND S.
LEVELS           118.0   119.4   111.4 107.4 103.4 98.4 91.4 84.4
MEDIAN ATTEN.      0.0     6.3     8.1  10.2  14.4 25.2 27.8 22.7
STANDARD DEVS.     0.0     7.9     7.3   6.3   6.8  8.5  7.2  9.4
OVERALL LEVEL DB(A) = 110.0
OVERALL LEVEL DIFF DB  =  12.0
LOWER QUARTILE PROTECTION DB(A) = 4.4
```

Sample output (cont'd)

```
            PROTN LEVEL DB(A)      PCT TOTAL RESID RISK
PCT TIME
WORN           LQ      MED                PEOPLE
100           4.4     8.9                53.9
99.5          4.3     8.8                54.7
99            4.3     8.7                55.4
97            4.2     8.1                57.9
95            4.0     7.7                59.8
90            3.7     6.7                63.4
75            2.8     4.6                69.9
50            1.7     2.5                75.6
```

is also shown in the figure. The computer program also calculates the reduction in ECSL (ie. protection) provided to the 25th centile and the 50th centile of the population of hearing protector users.

Assumptions underlying the Model

The model assumes that attenuation is normally distributed at each of the octave mid-band frequencies. Support for this assumption was presented in Appendix I. The model also assumes that all the variance in the attenuation data is produced by between-subject differences. However, in Appendix I it was shown that within-subject variance does contribute to the total variance in attenuation data. The model also assumes that the pth centile of the attenuation distributions at each test frequency are composed of the same individual hearing protector users. In Appendix I this assumption was shown to be valid for the lower centiles, but invalid for the higher centiles. This assumption was shown in Appendix I to result in the under-estimation of ECSLs for the higher centiles. The error in the higher centiles' attenuation estimates was not important in the discussion of selection procedures because the procedures use attenuation data drawn from the lower tail of the distributions. In the computer model, the whole distribution is utilised and therefore the ECSLs for the higher centiles will be under-estimated. Both of these assumptions lead to an under-estimation of the residual risk for the population of wearers.

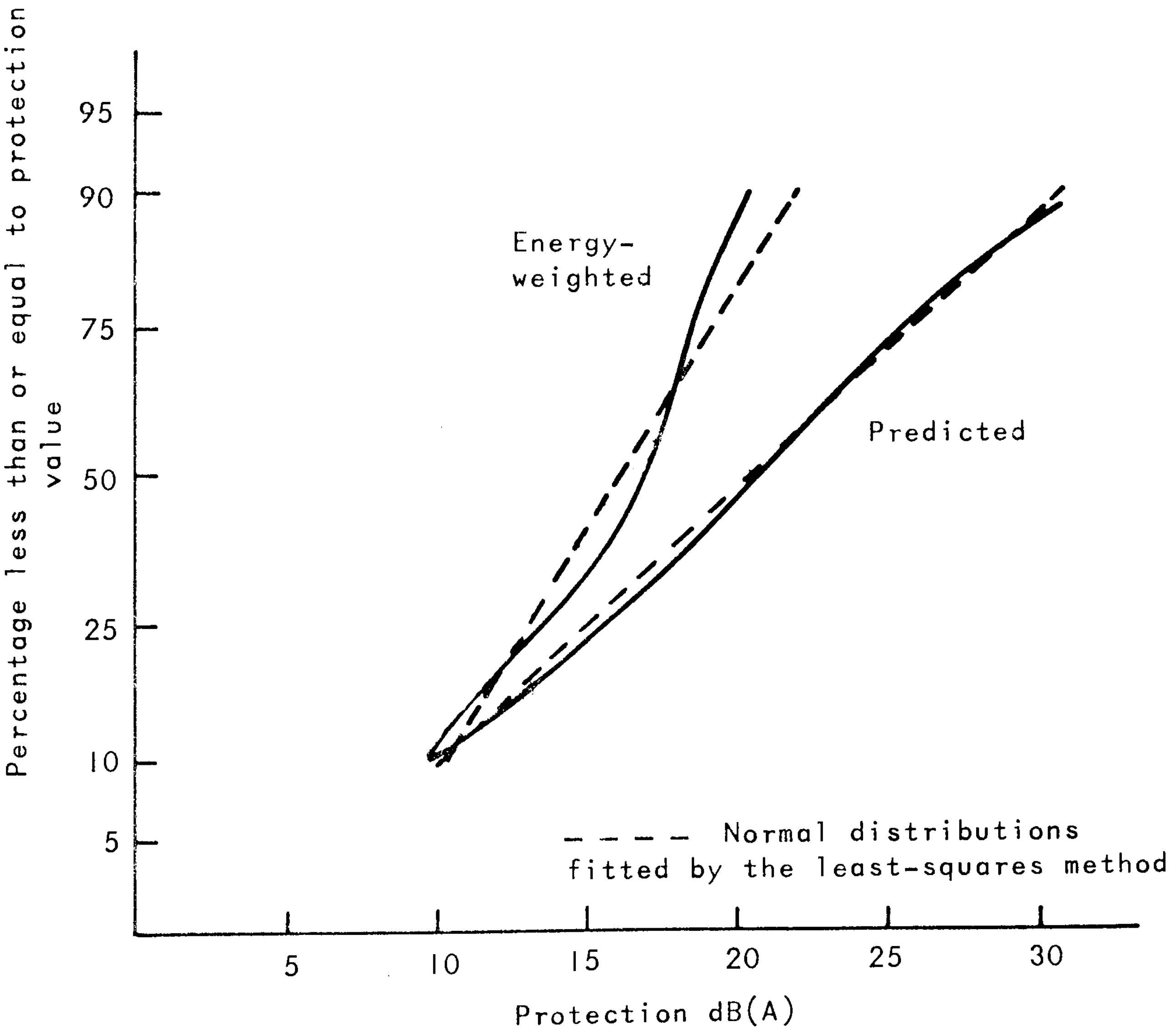
In Appendix I the errors in the estimation of protection which result from these assumptions were investigated. The raw data from attenuation tests on glass down earplugs (Appendix II) were applied to three noise spectra: a flat spectrum; a fast-rising spectrum (8dB/octave); and a fast-falling spectrum (8dB/octave).

The greatest errors resulted from the application of the data to the fast-rising spectrum. In Figure III-3, the cumulative distribution of protection is shown, where protection is defined as the reduction in ECSL provided by the hearing protectors, predicted from the attenuation data assuming that all variance in the data was produced by differences between subjects and that the pth centiles of the attenuation distribution at all frequencies were composed of the same subjects. Also shown in Figure III-3 is the cumulative distribution of protection obtained by applying each individual subject's attenuation test results to the fast-rising spectrum separately.

The two distributions have been fitted with normal distributions by a least-squares method; the best-fit normal distributions are illustrated in Figure III-3. The mean protection values from the best-fit normal distributions are 16.3dB(A) and 20.5dB(A), and the standard deviations 4.5dB(A)

FIGURE III-3

Cumulative Distributions of the Protection Provided by Glass Down Earplugs Against a Fast-Rising Spectrum of Noise: Energy-Weighted Estimates Compared with Distribution Predicted from the Assumption that All Variance produced by Differences Between Subjects



and 7.5dB(A) respectively.

The computer model has been used to estimate the effect of the differences between the two distributions of protection on the residual risk of $25\mathrm{dBHL}_{\overline{0.512}}$ for the hearing protector users. For this purpose, the following data have been applied to flat noise spectra with ECSL's within the range 95dB(A) to 120dB(A): -

(i) mean attenuation 16.3dB and standard deviation 4.5dB for each octave mid-band frequency

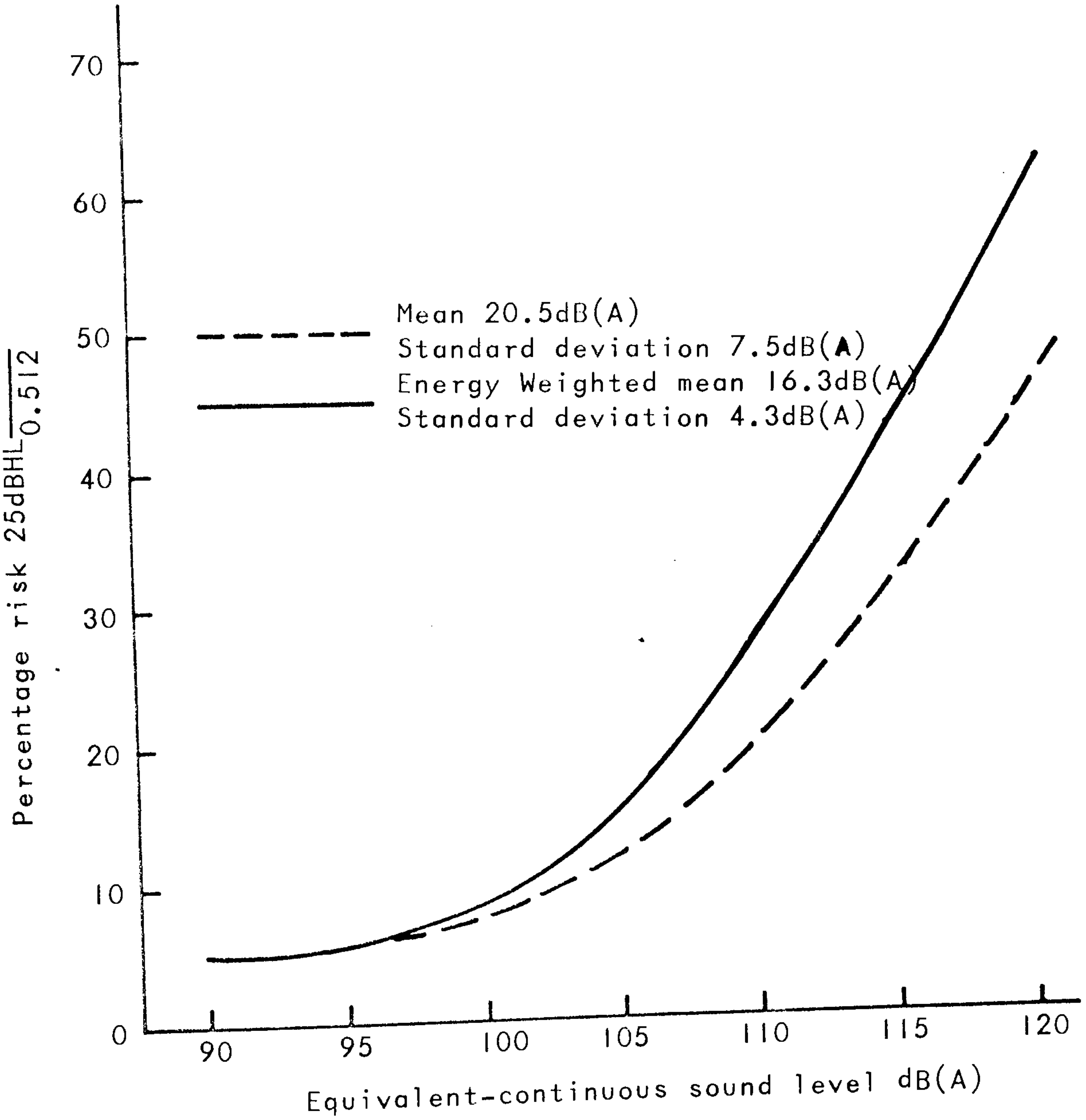
(ii) mean attenuation 20.5dB and standard deviation 7.5dB for each octave mid-band frequency

The results are displayed in Figure III-4.

Clearly, the assumption underlying the model can lead to an under-estimation of the residual risks for hearing protector users. The residual risk predicted by the model for glass down earplug users in an ECSL of 120dB(A) from a fast-rising spectrum is 47 percent, whereas when the assumptions are not made, a risk estimate of 61 per cent is obtained. However, it is unlikely that glass down earplugs would be chosen for such a high ECSL application, and the model is seen from Figure III-4 to under-estimate the risk less at lower ECSLs. For example, it is unlikely that glass down earplugs which provided a mean reduction in ECSL of 20.5dB(A) with a standard deviation of 7.5dB(A) would be selected for ECSLs much above 103dB(A), because the hearing protectors are usually chosen to reduce

FIGURE III-4

Residual Risk of Exceeding $25dBHL_{\overline{0.512}}$ for Glass Down Earplug Users Exposed to ECSLs Within Range 90dB(A) and 120dB(A) for Working Lifetime of 49 Years



ECSLs to 90dB(A) on the basis of lower quartile or mean minus one standard deviation attenuation estimates. From Figure III-4, it can be seen that the model under-estimates the risk by less than two percent for ECSLs below 103dB(A).

The residual risk curves in Figure III-4 have been calculated on the assumption that the earplugs are worn for the total duration of noise exposure. If the earplugs were worn for less than the total duration of exposure, the model would estimate the risk with greater precision. For example, in Figure III-4, for an ECSL of 110dB(A) the assumptions underlying clearly result in a seven percent under-estimate of residual risk. However, if the comparison were made on the assumption that the earplugs would only be worn for 95 percent of the noise exposure, the model would under-estimate the residual risk by only two percent.

Another potential source of error results from the use of a normal distribution of attenuation in the computer model. A limit has to be specified for the attenuation distribution. The specifying of a limiting attenuation at the lower centiles will result in at least one centile of the distribution always taking the lowest possible attenuation. This may lead to artificially high estimates of the risk, especially when high attenuation hearing protectors are worn against high ECSLs. Alternatively, it may result in artificial truncation of the attenuation distributions of hearing protectors with low attenuation.

Theoretical hearing protectors with flat attenuation spectra have been applied to flat noise spectra, to examine the effect of artificially fixing the lowest percentile attenuation to a specified limit. Attenuation spectra with mean attenuation of 30dB per octave and 15dB per octave, both with standard deviations of 5dB, have been applied to a noise of 120dB(A) and a noise of 90dB(A). The effect of specifying the lower limiting attenuation as -10dB, 0dB and +10dB was investigated and it was found that the residual risk estimate varied by less than one percent when lower limiting attenuations of -10dB and 0dB were used. Truncating the attenuation distributions at 10dB lowered the residual risk estimate by as much as 4 percent compared with the estimate obtained with a lower limiting attenuation of -10dB. The model has therefore been used with the lower limiting attenuation set to -10dB for all octave bands.

Summary

The model has been described with the assumptions that underly it. It is primarily a tool for investigating the trading relations between attenuation and the percentage of time that a hearing protector is worn in terms of the residual risk of hearing loss and the protection provided to a percentage of the wearers when the protectors are worn in particular noise spectra.

The accuracy of the estimates of residual risk provided by the computer model cannot be quantified precisely. The model is at the mercy of the errors inherent in the methods used to test attenuation, as well as the errors associated with the use of attenuation test data for estimating the reduction in level afforded throughout a noise spectrum. If the errors associated with the attenuation data and their application to noise spectra become available, perhaps a result of objective tests of noise levels under hearing protectors, the errors in residual risk could be estimated from Figure 3 and Figure 4 from Chapter 2.

APPENDIX IV

APPENDIX IV

SELECTION AND PROVISION OF HEARING PROTECTORS FOR EMPLOYEES IN A FOUNDRY FETTLING SHOP

In 1972 a large steel foundry chose to develop a general scheme for providing hearing protectors for employees exposed to noise levels exceeding the recommended limits (Department of Employment, 1972). They initially organised a pilot scheme to explore the problems involved. A small bay in one of the fettling shops in the foundry was chosen for the pilot scheme because the noise levels in the bay were among the highest encountered anywhere in the foundry.

By restricting the pilot scheme to a small area in which only twenty-three people were employed, it was hoped that a high degree of supervision could be exercised and that individual attention could be given to each of the men provided with hearing protectors.

The fettling shop was one in which the usage of other protective clothing such as respirators and eye protection was very high - the shop was often used as a model for other foundries on which to build their respiratory protection schemes.

The numbers of men involved in the various processes in the area covered by the pilot scheme are shown in Table IV-I

TABLE IV-I

Foundry Employees Involved in the Pilot Study: Processes and Associated Equivalent-Continuous Sound Levels

Process	No. involved in pilot scheme	Equivalent-continuous noise level (in dB(A)) Lower Estimate	Upper Estimate
Arc-Air Gouging	5	112	115
Dressing	8	120	123
Welding	2	95	95
Burning	2	102	104
Service Labouring	2	93	100
Automatic Shotblasting	1	96	97
Swing Frame Grinding	3	102	110

Personal Interviews

Before any noise measurements were made in the shop, each of the men was interviewed for about twenty minutes. The interview was designed to explore topics such as:

1. The working environment
2. The operations involved in the job
3. The pattern of work with respect to time
4. The other protective clothing that had to be worn for the job
5. The state of the man's hearing
6. The awareness of the man to the effects of noise on hearing
7. The man's attitude towards hearing protectors.

The information gained from the interviews was of considerable value when noise measurements were made and when exposure durations were calculated. The interviews also supplied information to be used in the selecting of hearing protectors.

Determination of Noise Exposures

Measurements of A-weighted noise levels and octave band analyses were made for each of the work positions - these are given in Table IV-2.The equivalent-continuous sound levels (ECSLs) were derived from the exposure durations estimated by the supervisors and the men themselves. The upper and lower

TABLE IV-2

Typical Noise Spectra for the Processes in the Fettling Shop

Process	Octave Band Sound Levels (dB) 63Hz	125Hz	250Hz	500Hz	1000Hz	2000Hz	4000Hz	8000Hz	Highest Measured Sound Level dB(A)
Arc-Air Gouging	84	87	94	95	98	102	103	101	117
Dressing	84	92	95	96	96	95	102	96	125
Welding	78	79	84	83	84	89	87	82	97*
Burning	85	87	93	92	92	98	96	93	106*
Service Labouring**									
Automatic shotblasting	84	90	96	91	84	83	81	75	97
Swing Frame Grinding	84	87	93	95	93	96	96	90	115*

* Highest noise levels quoted were produced by other noisy processes nearby.

** The service labourers could be exposed to the noise spectra from any of the processes.

bounds of their estimates have been used to produce upper and lower ECSL estimates presented in Table IV-1.

Selection of Hearing Protectors

Glass down earplugs were chosen for the service labourers, welders and shotblast operators. Lower quartile attenuation data and octave band noise spectra were used to calculate the reductions in noise level that would be provided against the particular noises; for these jobs glass down was calculated to reduce the ECSL below 90dB(A).

Analysis of the noise spectra for arc-air gouging, burning, swing-frame grinding and dressing showed that earmuffs would be required to reduce the ECSLs of the operators to 90dB(A). Six types of earmuff were chosen from the range available commercially (approximately thirty types were considered). The six were chosen on the basis of:

1. Ability to reduce the ECSLs to 90dB(A) calculated from lower quartile attenuation data and octave band noise spectra
2. Compatibility with the other protective clothing that had to be worn
3. Physical suitability of the hearing protectors for the wearing environment
4. Ease of cleaning and availability of replacement parts.

A pair-comparison test* was used with the six types of earmuff to obtain a ranking of preferences. Fifteen of the men from the pilot study were asked to adjust the muffs and

---

* Hays (1970)

try them on in a high background level of random noise. The men were told that the earmuffs had been chosen as adequate for the noise levels in the shop - the background noise was used so that the men could be sure that they were fitting the protectors properly. The men were highly consistent within their judgements; reasonably consistent agreement was obtained between the judgements of different men.

The earmuffs that were ranked overall second, third and fourth were chosen for distribution. The earmuffs ranked first overall, which were the most inexpensive available commercially, were not distributed because reports received at a late stage showed that they would probably have a very short life in a steel foundry environment.

Issue of Hearing Protectors

The glass down was supplied in boxes each containing two ready-made earplugs. The boxes of earplugs were available from the supervisor's office on request - the supply to each man was not limited in any way. The men were initially issued with glass down plugs during a personal interview. They were informed of: the need to wear the plugs; how to insert them; where to obtain them; and the importance of wearing them for the full duration of their exposure to noise.

The earmuffs were also issued during personal interviews. The men were given the opportunity to try on each of the three pairs of earmuffs in turn and to choose one pair. The men were informed of:the need to wear the earmuffs; how to adjust them to fit properly; and the importance of wearing them for the whole of their exposure to noise. The men could have their muffs cleaned at any time by taking them to the respirator cleaning room. The men were allowed to change to a different type of earmuff if they found the first issue unsatisfactory.

Hearing Protector Usage Six Weeks after Issue

The co-operation from the men was extremely good. They were interviewed within the first couple of days and again within two weeks of being issued with the protectors to gather their opinions of the protectors and the problems encountered with them. They were also visited on other occasions and after six weeks they were asked about their usage of the protectors.

Only one of the eight dressers said that he wore the earmuffs for most of the time. Four of the dressers said they wore the earmuffs when doing very noisy jobs* - three of these men said that they wore glass down earplugs for the rest of the time. Three of the dressers were no longer wearing any hearing protectors.

All three of the swing-frame grinders said that they wore

---

* Occasionally a batch of large flat resonant castings would be dressed. All the dressers said that these made more noise than the usual work.

the earmuffs most of the time, as did three of the five arc-air operators. The other arc-air operators and the two burners said they were no longer wearing any hearing protectors. About half of the group that had been given glass down earplugs said they were wearing them but the other half had given up wearing them.

The hearing protection scheme was based on a high degree of individual attention and enthusiasm but the degree of usage that was achieved differed little from that achieved by Heijbel (1961), Sugden (1967) and Lob (1971).

The pilot scheme was the basis of the scheme later used for providing hearing protectors to all persons with noisy jobs in the steel foundry.

APPENDIX V

APPENDIX V

SURVEY OF INDUSTRIAL NOISE SPECTRA

The attenuation provided by hearing protectors is a function of the shape of the frequency spectra of the noise in which they are worn. The accuracy of the hearing protector selection methods is also affected by the shape of the frequency spectra, as has been discussed in Appendix I.

Robinson (1968) reported surveys of more than 500 industrial noise spectra in the United Kingdom but the individual noise spectra were not quoted in his report. The gradients of the spectra were analysed by Robinson but the data were presented in summary form which was of insufficient detail to enable them to be used to calculate the attenuation that would be provided to the wearers of hearing protectors.

Presse, Rose and Murray (1962) listed more than 200 noise spectra in their report on noise in Australian industries. Unfortunately, the octave band analyses were not in the preferred frequency bands which have been internationally agreed (BSI, 1963). Therefore the data were not compatible with current attenuation data.

A programme was therefore organised to compile a data bank of industrial octave band noise spectra. The methods used for data collection are summarised below. The raw data have been utilised during the computer analyses described in

Chapters 2 and 6. The raw data have not been included in this appendix, although summaries of the spectra, which have also been used in Appendix 1, have been included.

Data Collection

Data collection took place during the period February 1973 to October 1973. Requests for assistance in compiling the data bank were widely distributed. Letters were sent to: -

(1) all industrial research and trade associations in the United Kingdom

(2) all members of the British Occupational Hygiene Society

(3) all medical officers and safety officers in the United Kingdom who were on the mailing list of the Safety and Hygiene Group

Two articles were published in health and safety journals to provide greater coverage and encourage interest in the survey. More than 850 letters were sent and replies were received to 44 percent of these. Many of the respondents were not able to provide octave band analyses but most wanted to be circulated with the results of the research. Data were supplied by approximately 200 organisations.

Most of the data were supplied on coding sheets circulated to respondents which were then indexed and input direct to the computer operators. Some respondents, however, supplied internal reports or published reports from which the data were extracted.

One large group of engineering companies, which recorded noise levels at all its factories, provided 800 octave band analyses in the form of a computer magnetic tape.

A total of 2640 octave band spectra were collated and stored in the data bank.

Summaries of Spectra in Data Bank

A-weighted sound levels

Interest in spectral distributions of industrial noises in which hearing protectors might have to be worn was the primary reason for collating the data bank. Respondents were therefore requested to provide only those spectra which would have sound levels in excess of 85dB(A).

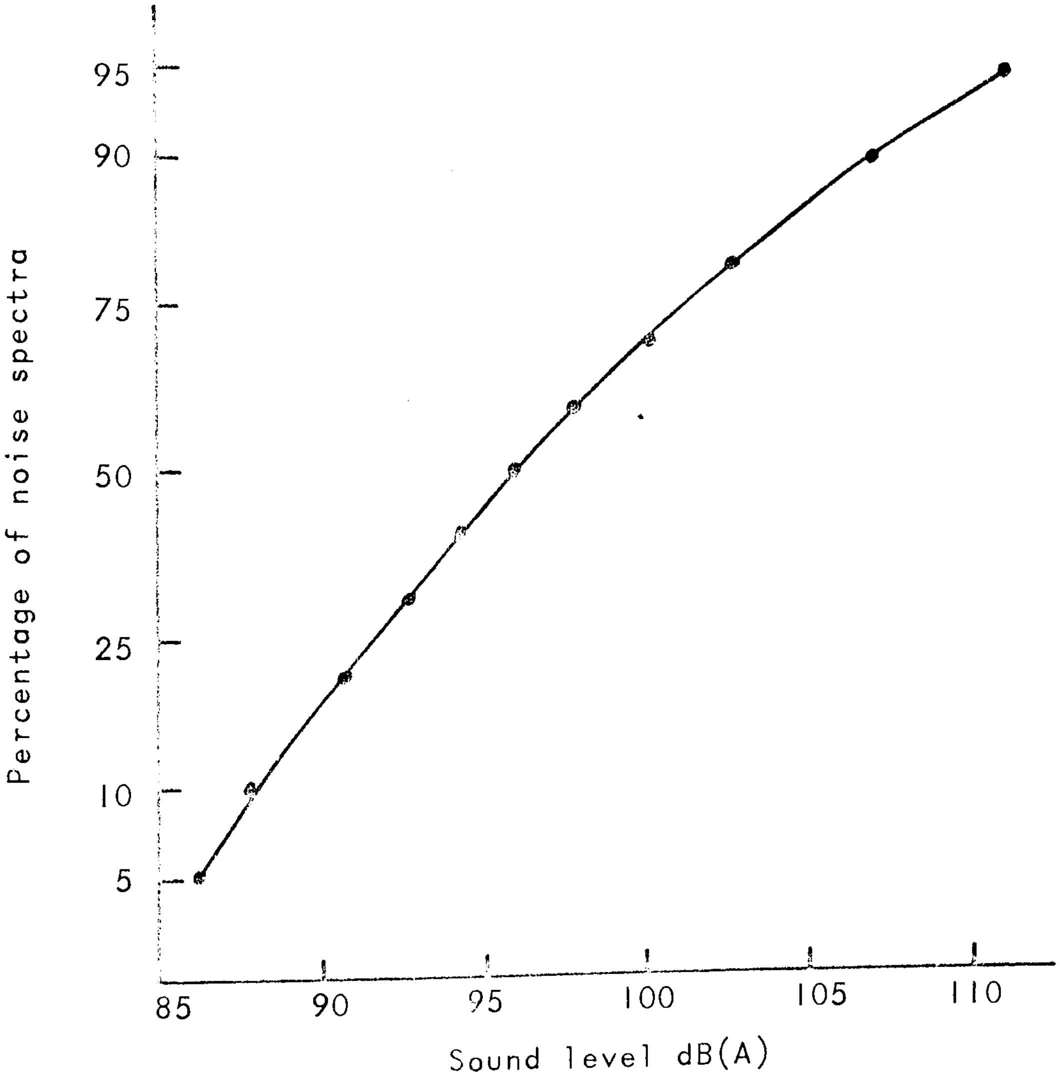
The organisation which provided 800 spectra on magnetic tape had, for their own reasons, normalised the data to approximately 85dB(A). These data have been extracted from the survey and the cumulative distribution of A-weighted sound levels for the remaining 1840 spectra displayed in Figure V-1.

Spectrum gradient

No single-figure descriptor can fully summarise the shape of an industrial noise spectrum because most industrial noise spectra exhibit non-uniform gradients throughout the audible

FIGURE V-1

Cumulative Distribution of A-weighted Sound Levels Calculated from the Survey of 1840 Octave-Band Analyses



frequency range. However, a widely-used descriptor of spectral gradient (S) has been developed by Robinson (1968):

$$S = \frac{1}{2}(L_{250} + L_{500}) - \frac{1}{2}(L_{2000} + L_{4000})$$

The octave band sound levels at 250Hz, 500Hz, 2000Hz and 4000Hz were chosen by Robinson because the octave bands above 5000Hz and below 250Hz rarely represented a significant contribution to the overall level in his sample of over 500 spectra.

The cumulative distribution of S, for the 2640 noise spectra, is illustrated in Figure V-2.

The "fasting falling" spectrum had a gradient of approximately 26dB per octave (S = -79). The "fastest rising" spectrum had a gradient of approximately 10dB per octave (S = 29).

Seven percent of the spectra in the data bank had steeper negative gradients than the "fastest falling" spectrum from Robinson's survey (S = -13). Four percent of the spectra had steeper positive gradients than the "fasting rising" spectrum from Robinson's survey (S = 15).

Differences between sound levels of adjacent octave bands

For each spectrum, the difference in levels (d) between adjacent octave bands was calculated:

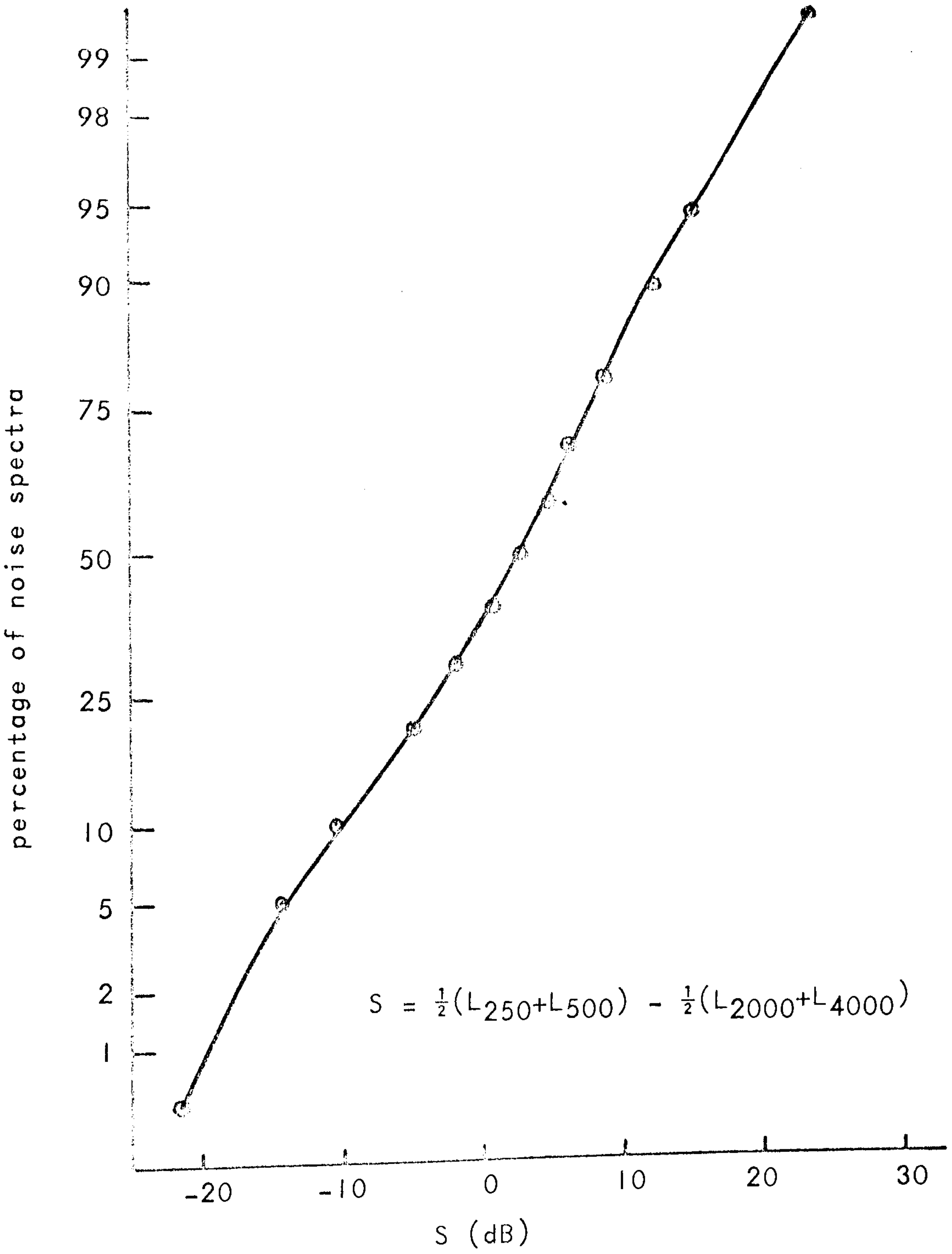
$$d_1 = L_{125} - L_{63}$$

$$d_2 = L_{250} - L_{125}$$

cont'd

FIGURE V-2

Cumulative Distribution of Spectrum Descriptor S from the Survey of 2640 Octave-Band Analyses



$$d_3 = L_{500} - L_{250}$$

$$d_4 = L_{1000} - L_{500}$$

$$d_5 = L_{2000} - L_{1000}$$

$$d_6 = L_{4000} - L_{2000}$$

$$d_7 = L_{8000} - L_{4000}$$

The cumulative distributions of d values are shown in Figures V-3,4,5 and 6.

The maximum and minimum values of d for the 2640 noise spectra are also indicated on Figures V-3,4,5 and 6.

FIGURE V-3

Cumulative Distributions of Difference Between Sound Levels of Adjacent Octave-Bands from the Survey of 2640 Industrial Noise Spectra: 63Hz - 125Hz and 125Hz - 250Hz

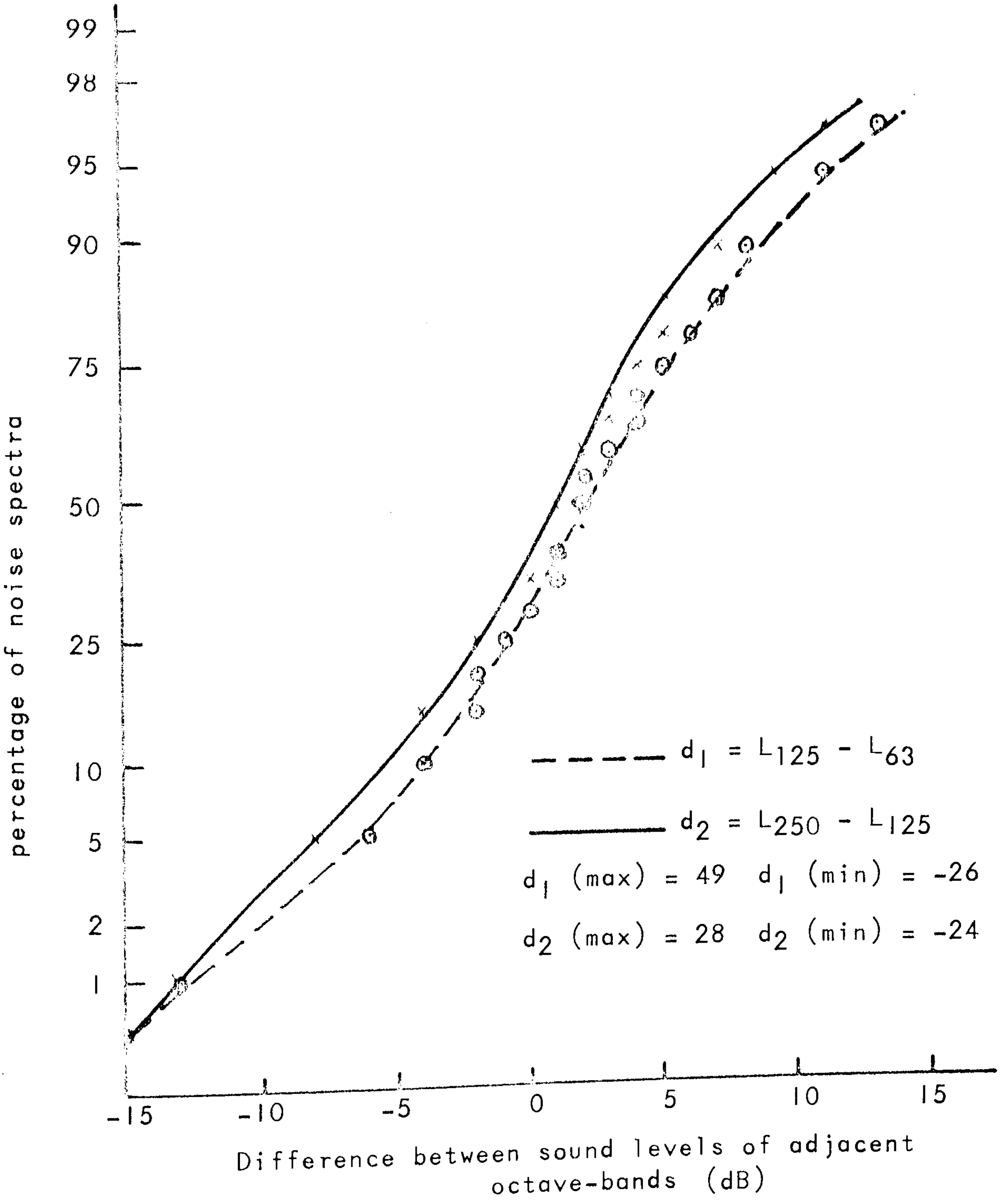


FIGURE V-4

Cumulative Distributions of Difference Between Sound Levels of Adjacent Octave-Bands from the Survey of 2640 Industrial Noise Spectra: 250Hz - 500Hz and 500Hz - 1000Hz

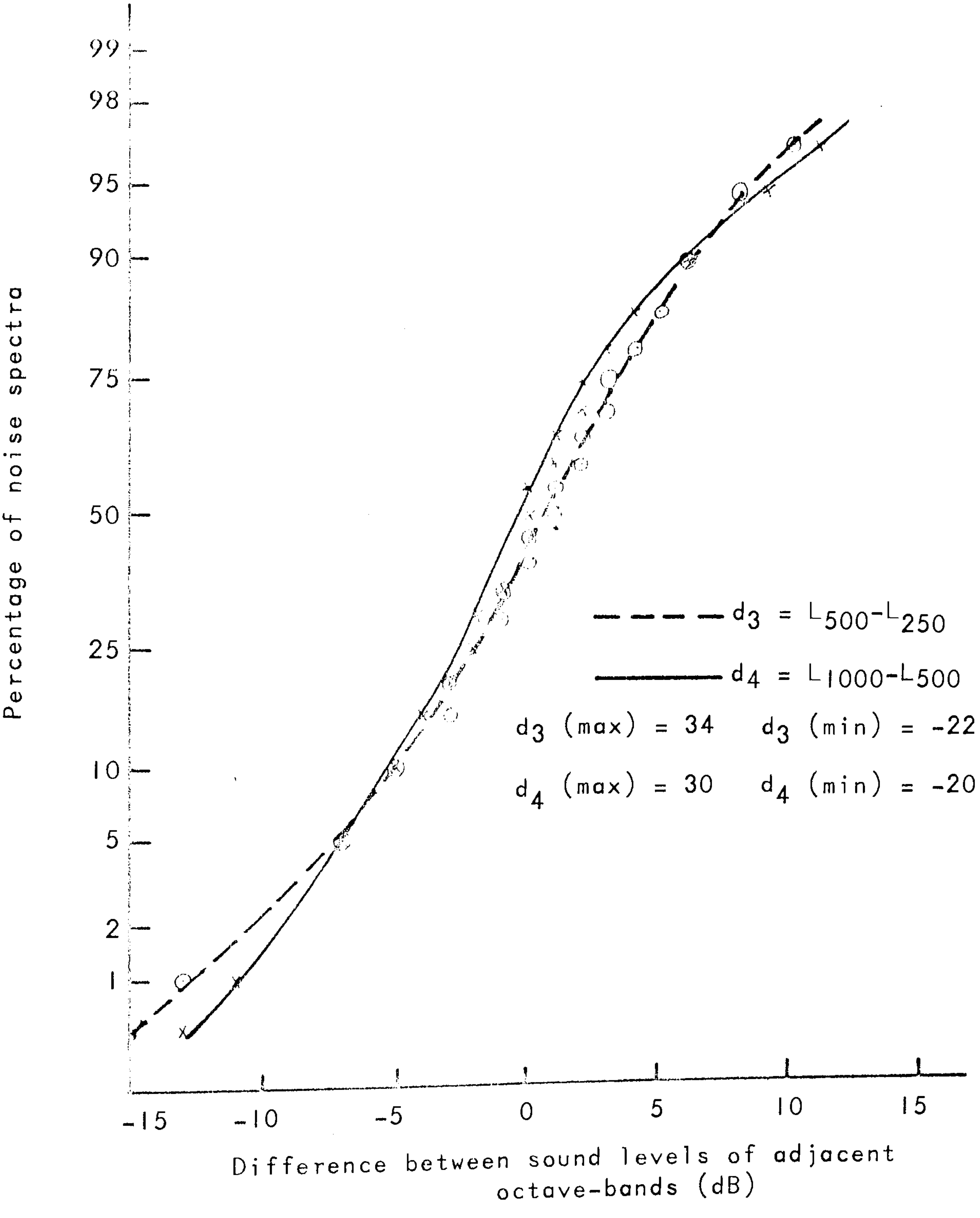


FIGURE V-5

Cumulative Distributions of Difference Between Sound Levels of Adjacent Octave-Bands from the Survey of 2640 Industrial Noise Spectra: 1000Hz - 2000Hz and 2000Hz- 4000Hz.

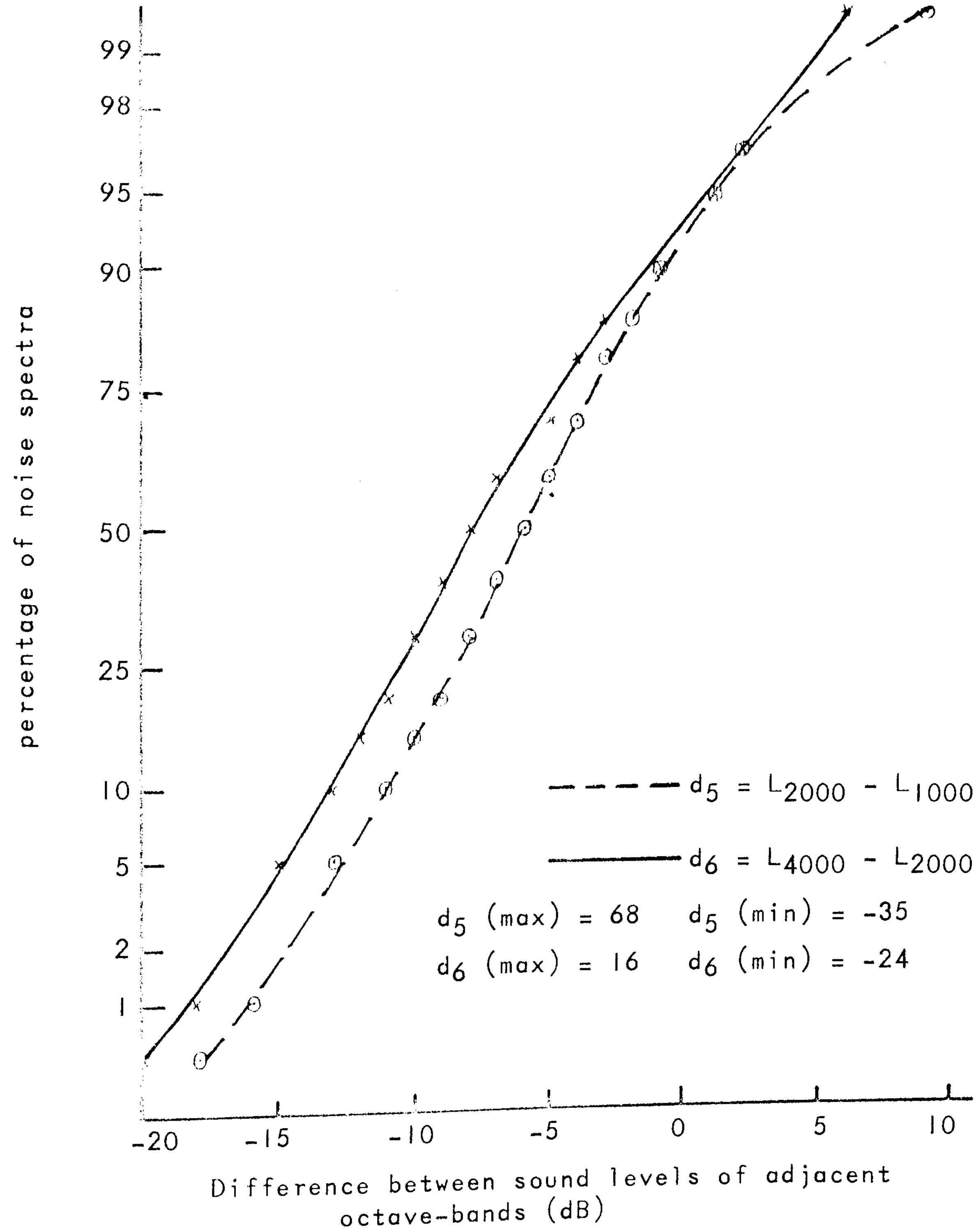
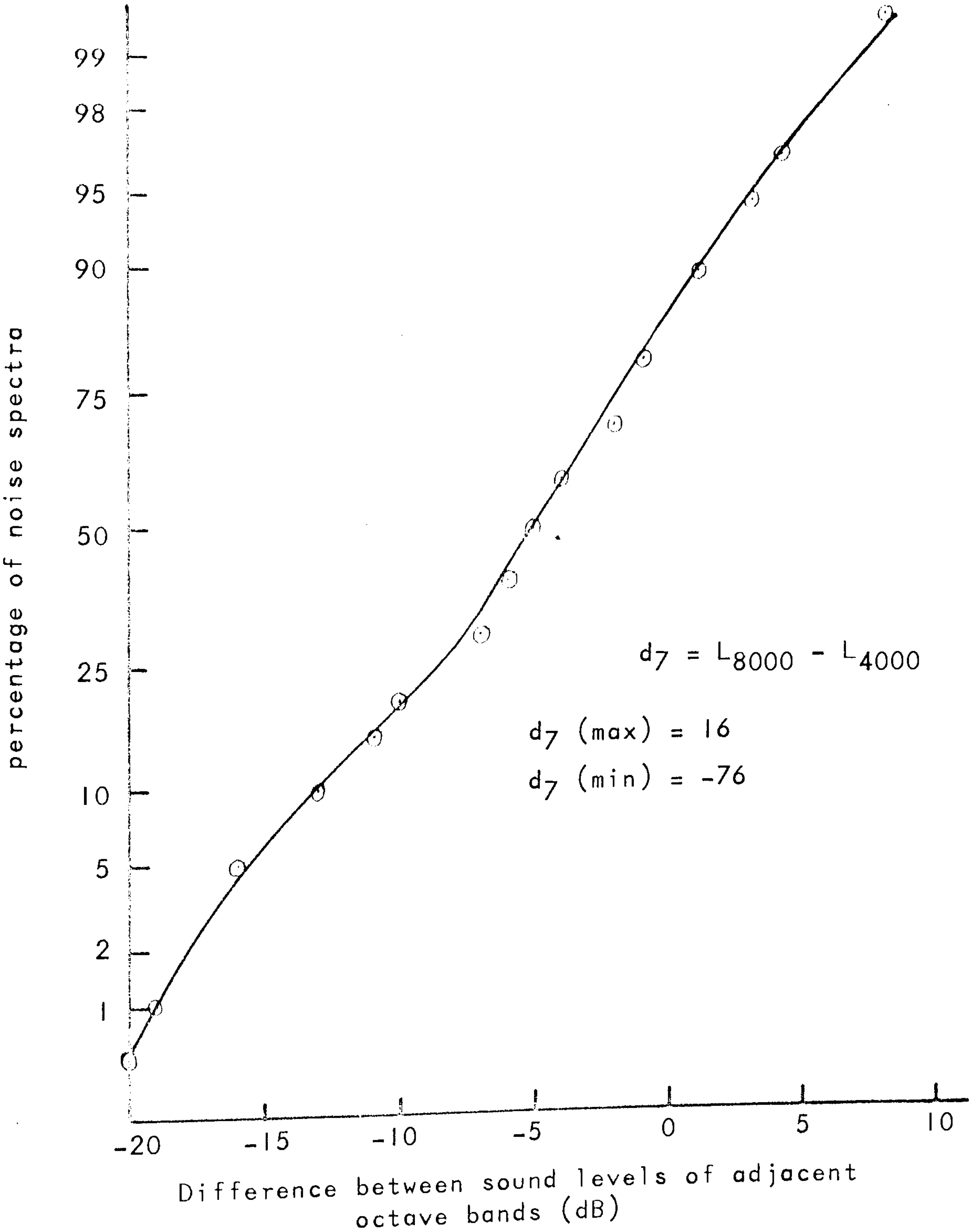


FIGURE V-6

Cumulative Distributions of Difference Between Sound Levels of Adjacent Octave-Bands from the Survey of 2640 Industrial Noise Spectra; 4000Hz - 8000Hz



APPENDIX VI

APPENDIX VI

DATA FROM THE LOCALISATION STUDIES AT A FOUNDRY

Table VI-1	Hearing levels of fettlers who took part in the localisation experiments
Table VI-2	Hearing levels of office employees who took part in the localisation experiments
Table VI-3	Angular response errors (degrees) made by twenty-one fettlers with unoccluded ears
Table VI-4	Angular response errors (degrees) made by twenty-one fettlers whilst wearing earplugs
Table VI-5	Angular response errors (degrees) made by twenty-one fettlers whilst wearing earmuffs
Table VI-6	Angular response errors (degrees) made by eighteen office employees with unoccluded ears
Table VI-7	Angular response errors (degrees) made by eighteen office employees whilst wearing earplugs
Table VI-8	Angular response errors (degrees) made by eighteen office employees whilst wearing earmuffs
Table VI-9	Time taken to respond to the warning shout by the twenty-one fettlers with unoccluded ears
Table VI-10	Time taken to respond to the warning shout by the twenty-one fettlers whilst wearing earplugs
Table VI-11	Time taken to respond to the warning shout by the twenty-one fettlers whilst wearing earmuffs
Table VI-12	Time taken to respond to the warning shout by the eighteen office employees with unoccluded ears
Table VI-13	Time taken to respond to the warning shout by the eighteen office employees whilst wearing earplugs

cont'd

Table VI-14 Time taken to respond to the warning shout by the eighteen office employees whilst wearing earmuffs

TABLE VI-I

Hearing Levels* of Fettlers Who Took Part in the Localisation Experiments

Subject	Left Ear Audiometric Frequency (kHz) 0.5	1	2	3	4	6	Right Ear Audiometric Frequency (kHz) 0.5	1	2	3	4	6	Average of both Ears $HL_{\overline{0.512}}$	$HL_{\overline{0.512346}}$
F1	23	16	18	27	45	32	22	11	23	28	42	28	18.8	26.2
F2	40	26	67	77	82	90	20	16	54	70	84	76	37.1	58.5
F3	52	26	54	70	76	72	43	24	45	66	76	77	40.6	56.7
F4	18	46	57	70	68	82	16	46	50	60	65	74	38.8	54.3
F5	8	10	17	54	61	47	16	13	26	33	45	36	15.0	30.5
F6	28	36	26	30	36	38	20	8	18	20	20	30	22.6	25.8
F7	24	10	20	50	52	48	26	12	29	48	44	30	20.1	32.7
F8	11	5	31	54	57	42	12	4	20	56	53	36	13.8	31.7
F9	12	3	2	12	8	26	22	4	5	6	15	22	7.7	11.2
F10	16	16	32	56	66	44	13	14	22	37	57	40	18.8	34.4
F11	6	7	32	36	36	30	10	3	33	42	40	26	15.1	25.1
F12	23	13	23	25	45	40	15	6	5	15	43	36	14.2	24.1
F13	17	7	6	18	30	45	17	17	6	17	26	14	11.6	18.3
F14	13	7	15	45	59	50	14	8	19	22	36	22	12.7	25.8
F15	18	43	50	53	43	34	20	8	15	40	40	30	25.6	32.8
F16	20	41	61	65	65	60	15	41	56	63	65	83	39.0	52.9
F17	27	23	48	75	53	38	17	46	67	87	90	80	37.9	54.2
F18	5	4	43	47	35	24	6	2	25	8	16	5	14.1	18.3
F19	18	25	63	68	73	65	17	20	66	80	75	82	34.8	54.3
F20	34	50	56	57	45	58	23	43	55	62	60	54	43.4	49.7
F21	11	9	7	30	18	23	10	6	6	30	20	17	8.1	15.5

* Hearing Levels (dB re ISO:R389, 1964) measured by Békésy audiometry using pulsed tones. Ambient noise levels inside the audiometric booth were not measured.

$HL_{\overline{0.512}}$ = hearing levels averaged over both ears at 500Hz, 1000Hz and 2000Hz

$HL_{\overline{0.512346}}$ = " " " " " " " 500Hz, 1000Hz, 2000Hz, 3000Hz, 4000Hz and 6000Hz.

TABLE VI-2

Hearing Levels* of Office Employees Who Took Part in the Localisation Experiments

Subject	Left Ear Audiometric Frequency (kHz)						Right Ear Audiometric Frequency (kHz)						Average of both Ears	
	0.5	1	2	3	4	6	0.5	1	2	3	4	6	$HL_{\overline{0.512}}$	$HL_{\overline{0.512346}}$
01	18	18	15	28	16	14	15	10	5	14	5	16	13.5	14.5
02	5	5	25	32	35	32	12	6	12	17	22	27	10.8	19.1
03	13	-5	0	-3	4	7	12	4	2	-3	1	6	4.3	3.2
04	12	2	2	4	14	6	20	5	0	5	13	17	6.8	8.3
05	21	20	5	16	15	10	13	8	4	5	12	0	11.8	10.7
06	12	2	-4	4	5	13	11	-10	-8	33	20	13	0.5	7.5
07	6	6	8	7	6	13	0	-3	0	0	-4	-4	2.8	3.1
08	16	15	11	10	11	11	12	10	9	10	10	25	12.1	12.5
09	17	15	24	12	6	24	13	10	19	6	4	23	16.3	14.4
010	23	23	22	21	15	27	6	0	-7	-4	4	2	11.2	10.7
011	14	23	21	33	26	38	18	15	12	33	40	36	17.1	25.7
012	8	10	0	0	6	7	5	5	0	0	6	0	4.6	3.9
013	15	10	-3	-4	2	7	15	4	5	6	14	20	7.7	7.6
014	7	10	15	16	24	20	5	6	3	8	11	25	7.6	12.5
015	8	6	5	-1	-2	-1	15	12	3	5	2	-4	8.1	4.0
016	15	0	0	2	10	20	11	5	0	3	4	-5	5.1	5.4
017	3	-5	0	2	15	20	26	26	23	20	23	28	12.1	15.0
018	16	15	13	23	23	18	15	7	6	10	8	-5	12.0	12.4

* Hearing levels (dB re ISO:R389, 1964) measured by Békésy audiometry using pulsed tones. Ambient noise levels inside the audiometric booth were not measured.

$HL_{\overline{0.512}}$ = hearing levels averaged over both ears at 500Hz, 1000Hz and 2000Hz.

$HL_{\overline{0.512346}}$ = " " " " " " " 500Hz, 1000Hz, 2000Hz, 3000Hz, 4000Hz and 6000Hz.

TABLE VI-3

Angular Response Error (degrees)

Fettlers Without Hearing Protectors

Subject	Background Sound Level 75dB(A) Stimulus Position									Background Sound Level 95dB(A) Stimulus Position								
	0	1	2	3	4	5	6	7	8	0	1	2	3	4	5	6	7	8
F1	1	46	3	40	2	4	34	14	21	132	18	45	27	55	22	12	47	62
F2	1	16	2	22	178	102	10	28	7	28	40	8	31	97	82	13	35	27
F3	2	40	0	50	12	14	25	12	30	47	49	3	46	40	58	18	23	72
F4	35	16	5	25	107	38	45	20	10	5	45	50	18	63	90	5	81	63
F5	2	65	0	20	160	15	7	25	30	145	129	55	20	4	7	15	45	90
F6	140	5	0	46	20	2	25	11	43	153	84	43	45	3	3	26	10	103
F7	2	19	2	14	7	116	14	22	30	149	4	17	44	156	80	9	70	120
F8	5	32	26	72	0	62	15	18	120	177	20	23	48	20	40	0	34	110
F9	73	80	7	30	4	103	7	3	140	180	173	10	23	46	11	12	22	135
F10	7	12	34	43	14	4	3	1	47	141	49	24	72	M	55	3	38	39
F11	0	5	12	50	37	4	25	23	130	145	22	2	53	45	25	19	22	110
F12	3	4	17	27	157	18	11	19	135	180	39	105	39	2	8	11	69	20
F13	25	57	5	66	120	7	9	31	57	37	38	26	95	22	1	40	63	47
F14	0	68	3	36	180	27	20	16	112	M	72	47	45	157	26	28	13	157
F15	175	6	20	46	2	38	5	5	26	176	90	13	6	84	64	61	44	125
F16	180	45	29	26	0	24	6	27	102	156	57	1	35	31	56	21	57	106
F17	178	31	10	58	168	64	28	23	55	153	24	43	16	M	57	3	89	69
F18	154	40	0	45	31	28	16	27	0	150	45	7	46	48	29	165	45	45
F19	3	45	2	36	70	152	23	18	30	2	48	3	41	M	115	28	15	36
F20	15	30	3	46	5	46	26	42	61	87	170	90	47	M	53	28	32	65
F21	180	65	21	4	155	22	10	38	116	149	67	30	21	25	27	29	90	101

M = No response

Angular Response Error (degrees)

Fettlers Wearing Earplugs

Subject	Background Sound Level 75dB(A)									Background Sound Level 95dB(A)								
	Stimulus Position									Stimulus Position								
	0	1	2	3	4	5	6	7	8	0	1	2	3	4	5	6	7	8
F1	180	15	2	45	2	38	25	20	23	177	72	37	28	67	24	115	18	158
F2	2	31	18	14	158	95	13	33	27	4	69	20	24	173	120	24	30	14
F3	175	45	2	41	18	2	26	25	110	180	63	2	39	117	10	11	18	90
F4	1	5	2	77	165	120	17	30	13	175	55	26	73	164	108	150	67	150
F5	82	42	7	39	2	14	1	75	157	130	40	150	12	20	10	1	83	130
F6	108	5	23	77	27	11	58	13	95	174	117	57	86	19	18	29	84	121
F7	2	90	1	7	3	108	35	6	118	170	20	40	20	16	18	3	5	0
F8	3	24	21	54	17	62	7	48	90	171	80	21	52	37	42	52	27	75
F9	1	25	5	42	0	3	6	10	22	180	28	24	5	1	0	5	37	165
F10	23	1	2	26	2	5	43	2	37	173	94	34	52	20	5	22	55	115
F11	178	41	3	50	29	9	19	24	133	176	42	1	46	24	3	32	20	131
F12	3	10	18	48	6	7	4	21	100	177	15	47	28	162	15	12	11	124
F13	22	25	1	43	140	8	9	55	85	110	38	2	60	M	2	48	15	120
F14	2	74	20	45	156	17	31	40	175	177	96	30	46	180	45	7	34	177
F15	177	42	31	22	1	1	6	13	159	157	130	131	31	45	61	14	1	90
F16	161	15	9	49	5	4	15	49	125	133	163	140	67	M	36	10	52	110
F17	11	65	28	4	60	38	2	29	174	M	180	10	110	M	M	14	112	M
F18	165	45	2	25	9	38	20	27	40	140	40	172	44	22	27	19	27	119
F19	2	42	7	32	165	120	39	6	10	84	0	3	51	M	157	167	23	18
F20	88	75	9	20	70	68	15	25	73	92	175	11	32	M	57	30	20	117
F21	4	41	8	18	32	37	2	59	140	174	57	13	2	M	5	28	25	128

M = No response

TABLE VI-5

Angular Response Error (degrees)

Fettlers Wearing Earmuffs

Subject	Background Sound Level 75dB(A) Stimulus Position									Background Sound Level 95dB(A) Stimulus Position								
	0	1	2	3	4	5	6	7	8	0	1	2	3	4	5	6	7	8
F1	2	18	2	42	20	15	27	20	22	163	47	21	11	35	25	68	20	22
F2	0	49	0	45	175	67	22	28	15	7	45	178	26	88	157	20	27	16
F3	0	12	134	33	55	57	150	90	62	112	38	6	48	101	70	3	110	115
F4	6	20	14	0	175	40	26	77	6	72	M	45	M	M	M	M	M	M
F5	145	75	15	14	0	20	13	32	87	157	45	132	7	30	22	15	30	112
F6	180	12	32	24	19	5	20	19	122	M	M	28	97	150	1	19	25	102
F7	2	3	60	46	34	6	36	30	120	175	46	113	8	M	75	14	157	73
F8	3	28	15	60	40	48	20	50	119	148	27	123	100	13	33	15	23	147
F9	174	2	10	10	175	3	6	2	136	147	85	22	12	39	18	4	27	170
F10	143	22	8	14	36	0	51	15	102	123	175	31	3	55	27	37	157	M
F11	2	42	7	4	3	11	25	22	117	157	37	8	13	2	27	15	21	140
F12	2	3	9	17	173	14	23	23	19	60	65	33	48	M	13	21	28	110
F13	137	69	7	48	38	22	3	51	110	162	160	160	50	36	0	8	88	M
F14	179	39	0	48	0	12	3	23	112	3	25	23	97	2	24	2	54	154
F15	178	22	22	48	1	47	16	44	53	148	138	157	27	27	11	66	M	98
F16	178	27	4	54	M	5	23	64	110	M	M	M	M	M	M	M	M	M
F17	130	105	53	133	20	88	40	43	81	145	167	115	70	M	M	45	90	174
F18	145	44	0	42	28	16	8	32	75	97	39	0	45	49	58	160	40	113
F19	20	18	7	31	180	88	29	2	10	7	29	7	40	180	150	159	36	42
F20	47	69	3	57	167	67	23	45	64	M	38	7	143	M	M	M	M	M
F21	10	57	4	15	121	22	20	50	32	140	127	36	2	38	62	38	28	158

M = No response

Angular Response Error (degrees)

Office Employees Without Hearing Protectors

Subject	Background Sound Level 75dB(A) Stimulus Position									Background Sound Level 95dB(A) Stimulus Position								
	0	1	2	3	4	5	6	7	8	0	1	2	3	4	5	6	7	8
01	35	2	9	35	145	90	4	26	40	135	3	8	32	40	47	2	53	126
02	2	25	5	20	10	6	2	40	25	14	60	16	7	20	0	100	40	165
03	0	16	20	53	2	24	35	2	84	130	61	33	67	178	105	25	4	135
04	175	28	0	49	14	38	23	7	105	163	70	9	40	5	72	45	5	92
05	175	25	3	48	0	4	26	13	58	177	16	86	77	33	13	24	3	126
06	147	45	37	28	12	33	11	11	35	156	35	0	6	40	8	0	56	85
07	177	3	0	73	167	3	3	3	21	20	70	36	17	5	3	10	15	85
08	4	37	15	27	9	35	20	19	83	135	42	4	27	M	28	8	28	100
09	2	18	1	45	2	18	6	28	19	149	24	10	3	M	68	160	62	164
010	22	100	2	27	0	19	36	17	119	122	50	34	1	12	22	68	111	166
011	164	13	7	17	1	9	2	47	105	180	79	9	28	28	27	70	36	58
012	6	19	11	49	20	17	5	22	23	155	58	14	63	22	14	70	15	144
013	6	8	26	86	167	17	5	9	17	7	42	12	115	118	11	172	90	46
014	27	20	3	61	40	17	18	3	17	102	18	6	45	47	112	95	118	124
015	2	22	29	48	180	114	20	23	1	112	8	12	82	155	33	9	9	105
016	9	7	18	14	105	95	11	15	4	30	46	122	22	17	88	20	5	70
017	180	5	23	47	22	10	30	17	15	153	8	101	84	26	22	3	58	141
018	25	10	26	74	169	102	20	15	34	M	18	37	100	31	109	39	4	95

M = No response

TABLE VI-7

Angular Response Error (degrees)

Office Employees Wearing Earplugs

Subject	Background Sound Level 75dB(A) Stimulus Position									Background Sound Level 95dB(A) Stimulus Position								
	0	1	2	3	4	5	6	7	8	0	1	2	3	4	5	6	7	8
01	24	6	32	27	147	36	16	44	34	163	57	33	36	35	64	23	34	110
02	33	22	7	45	146	92	6	34	95	148	44	27	24	165	110	24	40	11
03	15	13	3	42	178	4	20	16	135	3	21	14	9	173	169	68	11	120
04	9	33	10	39	177	38	24	18	132	4	52	4	45	20	40	20	20	45
05	178	30	10	44	18	41	12	8	35	120	22	11	8	49	50	18	6	131
06	163	65	18	10	36	20	27	41	43	178	109	12	26	22	48	38	33	108
07	3	10	18	10	2	13	10	22	0	179	2	2	73	44	45	10	13	30
08	158	1	29	28	15	14	15	42	36	178	63	32	28	M	106	12	47	131
09	3	40	5	46	2	27	9	52	20	44	30	2	20	M	22	26	41	122
010	177	43	9	22	1	58	18	18	97	179	82	35	30	1	24	22	29	114
011	177	68	18	7	0	33	12	23	127	169	83	34	54	20	10	51	21	160
012	0	40	13	26	3	47	13	5	22	155	49	25	27	4	22	14	12	165
013	3	18	25	104	166	7	0	61	3	175	23	16	28	M	60	70	56	11
014	32	41	6	50	36	29	27	33	92	28	47	13	64	5	16	10	60	28
015	137	33	19	41	23	26	20	22	17	18	65	39	58	67	108	3	37	37
016	179	50	4	52	9	40	37	15	40	177	78	4	33	11	38	135	59	93
017	2	3	18	61	14	127	31	0	24	155	41	22	50	12	9	5	64	118
018	17	5	8	39	176	49	3	13	33	14	22	19	57	177	115	2	16	115

M = No response

TABLE VI-8

Angular Response Error (degrees)

Office Employees Wearing Earmuffs

Subject	Background Sound Level 75dB(A)									Background Sound Level 95dB(A)								
	Stimulus Position									Stimulus Position								
	0	1	2	3	4	5	6	7	8	0	1	2	3	4	5	6	7	8
01	154	8	10	31	0	102	8	37	90	140	177	32	19	27	45	5	136	110
02	176	27	2	65	156	18	15	67	9	66	30	19	53	143	43	10	45	105
03	6	23	18	72	5	7	7	21	52	70	84	132	45	68	158	158	64	90
04	175	32	13	52	46	32	40	2	103	150	33	11	59	105	96	45	2	90
05	178	30	11	22	10	3	8	20	86	155	176	15	172	8	38	12	44	74
06	160	57	31	46	37	3	2	7	68	152	38	25	21	63	129	177	180	97
07	12	39	2	58	165	108	13	20	4	141	94	3	65	18	167	14	57	167
08	180	75	33	38	4	39	12	29	105	155	94	22	4	55	6	72	65	158
09	4	41	4	49	35	100	10	42	2	19	87	6	110	152	7	26	62	166
010	20	38	36	37	5	45	44	31	38	176	154	34	6	M	3	160	57	158
011	169	92	9	5	28	56	96	145	176	176	63	30	40	25	32	82	155	166
012	19	19	18	38	173	30	27	4	20	113	139	41	94	84	118	27	9	71
013	11	36	54	39	161	136	2	16	25	1	7	51	3	107	141	7	2	113
014	149	28	17	63	52	22	42	34	9	177	57	13	63	13	90	114	167	164
015	13	31	3	65	131	56	30	2	21	145	79	42	11	M	70	17	58	91
016	8	50	9	41	3	84	24	13	41	180	127	5	33	19	42	63	126	M
017	6	16	15	92	22	56	8	9	7	150	23	138	3	27	129	28	145	165
018	14	16	19	33	164	27	1	19	9	23	115	140	40	M	23	13	4	112

M = No response

TABLE VI-9

Time taken to Respond to the Warning Shout (milliseconds)

Fettlers without Hearing Protectors

Subject	Background Sound Level 75dB(A) Stimulus Position 0	1	2	3	4	5	6	7	8	Background Sound Level 95dB(A) Stimulus Position 0	1	2	3	4	5	6	7	8
F1	6007	2764	2914	4220	4691	5727	2734	5231	6721	4130	2808	6909	4487	3887	4162	3650	8173	5801
F2	5606	5157	6001	5579	3516	5895	2840	4680	2959	4670	4511	4563	4352	4894	5712	4487	8179	4648
F3	4101	1958	2241	2053	4008	2305	2268	2158	5519	6034	2109	2241	2077	2876	6458	2603	2267	3608
F4	3835	2438	2030	2507	3193	2549	2997	2479	4042	4033	2139	3852	2327	2889	4553	5185	4142	4663
F5	2329	3037	3152	1971	4257	1943	3058	3066	2539	2995	2033	2479	2002	2033	2592	2393	2295	2228
F6	5839	4553	4499	3787	3045	5415	2782	3199	4281	E	2439	4281	5292	3700	5081	2607	3708	5964
F7	3182	4125	3111	3522	3502	3498	4716	3076	3383	4744	5063	3568	7076	4058	3591	3394	3861	7040
F8	3046	2201	2287	2149	3293	3256	2617	2440	3692	3108	2337	2164	2477	3013	3156	2534	2335	2939
F9	3468	2340	2151	2793	3450	3850	2149	2731	4507	2190	3822	3519	1922	2629	3349	2285	4110	7036
F10	5223	5860	5239	4366	4347	2692	5140	4855	5264	3880	3521	2546	4341	M	3231	3674	3218	2327
F11	2398	3224	2595	1871	3178	2746	2297	2235	2824	2553	2472	2697	2092	2853	2780	3524	2462	2451
F12	2715	2180	2187	2038	4137	3001	2453	2197	2397	3226	2206	2882	2337	2801	3781	2247	2221	2765
F13	2647	2853	2072	2439	2775	2519	2318	2396	2541	2712	2356	2644	3148	3213	2708	2673	2449	2871
F14	3169	4011	3984	2696	3613	2527	3101	2404	5321	M	E	4535	2533	5553	4458	2614	3634	3822
F15	1796	2090	1973	2075	1795	2402	2072	1995	2983	2137	1762	2786	1814	3018	2109	2480	2094	2499
F16	2580	2501	2004	2527	3002	2602	2484	2576	2938	2703	2025	2362	1951	2718	2801	2513	2454	2514
F17	3379	2288	1942	2814	3252	2498	1880	2650	2645	3723	2367	2516	2570	M	3188	2440	2820	3373
F18	3621	3027	2427	1885	2264	2259	2250	2165	3292	3392	2268	2199	E	3065	2301	3504	3208	5809
F19	4019	2870	2602	2168	12590	4067	2643	3341	3364	3287	2369	2420	2295	M	2863	E	3206	3387
F20	2605	2310	4823	3136	2392	6291	2194	3914	3318	2867	2965	5642	4376	M	2516	4634	4510	3272
F21	7209	5837	2963	2121	8588	356	3100	4941	3807	4925	E	3074	3121	4842	4306	3028	3981	3172

M = No response
E = Response time not recorded

TABLE VI-10

Time Taken to Respond to the Warning Shout (milliseconds)

Fettlers Wearing Earplugs

Subject	Background Sound Level 75dB(A) Stimulus Position 0	1	2	3	4	5	6	7	8	Background Sound Level 95dB(A) Stimulus Position 0	1	2	3	4	5	6	7	8
F1	5000	4492	2482	4390	5142	5762	7925	5042	6584	7660	5652	4649	5292	14557	E	6330	8415	6022
F2	2648	5636	2186	3541	2420	2904	3031	2593	2734	4615	3217	3071	4359	5641	3992	3745	3298	4662
F3	3422	2217	2163	2222	5745	2945	1986	3350	2353	2691	3921	2003	2923	5901	4851	3327	2200	5669
F4	3716	3260	2933	4402	5687	4504	2877	5276	3532	2421	3066	6039	3127	3604	6885	5377	6005	3772
F5	2509	2640	2433	2741	1918	2221	2472	2344	2916	2707	2796	2313	1978	3064	1957	2532	2030	2472
F6	3543	3175	7053	74	5967	4016	3425	5064	4713	2852	3747	4829	3271	8032	5669	4802	5104	4100
F7	3898	4628	2805	3868	7460	3180	4204	4203	4535	5542	9704	3440	3355	4901	5490	4729	4887	10513
F8	3496	2866	2642	2474	3117	2263	2688	2843	2808	4742	3273	2833	2806	6426	3203	5166	2784	4026
F9	4034	2376	2580	2637	3718	2674	2076	3315	3809	3335	3660	2920	2152	2850	3162	2176	2453	3067
F10	4052	2661	4496	2555	2381	3409	2803	2344	3735	2446	2572	3040	3447	3735	2909	3090	3358	2367
F11	4114	2457	2226	2320	2678	2945	3129	3002	4583	3398	2390	2511	2059	5004	3184	5768	3214	2943
F12	2593	2443	3320	3318	2032	2585	2972	2503	3278	2567	5711	2561	2682	6565	2401	2373	2249	3544
F13	2949	2087	2013	1934	2198	2269	2219	2348	2062	2476	2245	2132	2142	M	3262	2602	2949	2866
F14	3142	2853	3034	2238	2846	2566	2078	2615	5982	4919	2709	2925	2358	2842	3112	3647	3032	3296
F15	2267	1780	2084	3093	1870	2343	2291	2698	1950	2849	2352	E	2174	2290	2359	2221	2531	2047
F16	2513	2298	2098	1987	2532	2595	3336	2635	2910	2989	2615	1550	2545	M	3976	2833	4064	3460
F17	5132	3054	2887	2247	2780	2698	2671	2671	3482	M	2562	3362	3301	M	M	2690	E	M
F18	9564	2068	2254	2507	2860	2779	2151	2261	3979	3172	2062	2528	2171	5964	4063	2464	2613	5232
F19	2277	2522	2858	3585	3664	E	2642	2912	2962	2951	3556	2715	3675	M	9706	3834	2391	3466
F20	7349	2143	3696	2672	5861	3881	3038	2609	4040	2757	3826	2752	2856	M	3418	3573	5157	8752
F21	4098	2958	2478	2855	4515	4613	1381	2967	2776	3504	4030	4721	3304	M	3995	2422	2997	4180

M = No response E = Response time not recorded

Time Taken to Respond to the Warning Shout (milliseconds)

Fettlers Wearing Earmuffs

Subject	Background Sound Level 75dB(A)									Background Sound Level 95dB(A)								
	Stimulus Position									Stimulus Position								
	0	1	2	3	4	5	6	7	8	0	1	2	3	4	5	6	7	8
F1	5009	4411	3652	3857	4720	3218	4699	6250	3844	13470	3998	7954	7104	10048	3833	6380	4308	4481
F2	2881	3071	3260	2991	4480	3375	2745	3074	3388	3329	2792	3653	4391	8228	4512	3938	5285	4867
F3	4586	3129	2531	3079	2830	3988	2632	3494	2993	3401	3180	2231	6101	3780	3844	3260	2639	3045
F4	2871	2641	2880	1641	2615	4233	2403	2213	3232	3083	M	3078	M	M	M	M	M	M
F5	5172	3023	2356	1946	2271	2161	2661	2791	2450	2892	2931	2934	2514	4668	3991	3697	3181	4216
F6	3737	E	6860	4768	4164	5348	2699	8	4507	M	M	5806	3587	7400	4781	364	3467	5064
F7	4157	3399	4103	3051	5541	4220	2941	4661	E	4082	2975	7514	4134	M	3391	5301	6873	3564
F8	3466	2375	2435	3152	3198	2766	2364	2577	3987	3588	2738	3261	2815	3603	2967	2828	2950	5122
F9	2807	2722	2182	3084	4914	5922	2676	2872	4069	2945	3892	2341	2472	3270	3830	2195	2458	4653
F10	4053	7761	3414	3967	3018	2825	3399	3628	4383	3190	3941	3395	5035	3220	3342	6978	4076	M
F11	2349	3448	3308	3494	6541	5234	2447	3587	3486	3980	3469	2723	4973	3122	6095	2247	3036	13297
F12	3106	2587	2275	1938	2664	2994	3951	2054	2731	2703	2309	2167	3663	M	2190	2308	3242	2722
F13	2678	2782	2223	1937	3269	2221	2553	2621	2393	3283	2841	2598	3161	3400	4018	3991	3858	M
F14	2842	3403	2131	2180	3091	2296	2113	2398	3167	3208	2619	3313	2628	5194	2482	2578	2994	5631
F15	1722	2410	2099	1939	2064	2050	2116	1932	2526	2903	2127	2627	2145	6479	2391	2044	M	3798
F16	E	2048	1950	1753	M	2489	2268	2280	2425	M	M	M	M	M	M	M	M	M
F17	3866	4413	6310	2456	3846	3381	2545	3067	E	6566	3461	3047	7407	M	M	3104	4789	4752
F18	5116	2234	2124	2510	4203	3003	2446	2355	3101	3168	2201	2356	2397	3019	3123	2678	2751	5271
F19	2747	2855	2304	2858	2275	3712	2613	2446	2828	4103	2532	2940	4160	4358	3514	3666	4547	3483
F20	4713	6126	3220	4550	7461	2298	3653	4729	4687	M	4412	4168	4670	M	M	M	M	M
F21	5772	3756	E	2535	10448	3198	6654	3346	5307	E	4509	4650	3689	3568	E	4545	9006	4767

M = No response
E = Response time not recorded

TABLE VI-12

Time Taken to Respond to the Warning Shout (milliseconds)

Office Employees without Hearing Protectors

Subject	Background Sound Level 75dB(A) Stimulus Position 0	1	2	3	4	5	6	7	8	Background Sound Level 95dB(A) Stimulus Position 0	1	2	3	4	5	6	7	8
01	2809	2502	2839	2000	3595	3824	2025	2006	2321	2122	3587	2052	2148	4791	2450	2102	2973	2836
02	5021	4826	5804	5139	E	3632	E	5835	E	E	4748	5061	3624	E	E	E	6571	6400
03	2610	2367	2680	5248	2827	2449	E	2744	7411	5143	4043	2460	3266	5273	4669	4050	2772	8899
04	4573	3357	2707	7004	3647	3673	2838	3280	4175	4685	2970	2954	2517	9388	4780	4213	2759	2807
05	3127	3764	3994	3569	3747	3398	4083	5603	4303	4631	3853	6536	4779	4043	4833	4520	4578	3425
06	3464	3243	5289	2249	3008	4903	4286	4006	3692	4279	3117	2937	1605	3430	2580	2735	4899	3237
07	2994	2480	2014	2079	2953	2238	2155	2318	2544	8920	2825	2984	2772	4163	3298	2695	2086	2946
08	1707	1696	1987	1729	1954	1689	1729	1678	2161	2112	1985	1636	1773	M	1976	1962	1998	2186
09	2840	2706	2236	2461	7997	3472	4440	4635	3024	6325	3038	2575	4111	M	E	9230	3249	7497
010	5554	2613	1651	2457	2928	3228	1866	1587	2014	9222	1551	1817	1866	2691	2241	2165	2531	1768
011	1989	2116	1645	1963	1918	1859	1818	1808	2153	2049	1979	1953	1859	2025	2104	1987	1780	2071
012	5340	6380	3816	2672	2768	4618	2814	2444	2184	3486	2907	5624	2274	3771	2191	2899	3664	4935
013	3283	3684	2311	3375	E	6939	3560	4189	2839	3198	4495	3545	5171	5399	3167	3452	3951	4884
014	1861	1902	1895	1923	2243	2073	1759	1791	2001	2291	2023	2240	2128	2875	2294	2532	2391	2293
015	2413	1671	1805	1670	2404	2361	2888	1836	2345	2482	1936	1802	2029	2820	3197	2116	2552	3256
016	1852	1954	1930	2081	2087	2451	2572	1995	1987	1976	2334	2391	1970	2321	2049	2247	2240	2768
017	8468	1643	2496	2237	3194	2902	2089	1772	3158	5199	2451	8890	3712	2932	3095	3453	1882	3331
018	3756	2023	3719	2434	2635	2540	3184	2909	2809	M	2684	2483	2036	3299	2477	2664	2495	2887

M = No response
E = Response time not recorded

TABLE VI-13

Time Taken to Respond to the Warning Shout (milliseconds)

Office Employees Wearing Earplugs

Subject	Background Sound Level 75dB(A)									Background Sound Level 95dB(A)								
	Stimulus Position									Stimulus Position								
	0	1	2	3	4	5	6	7	8	0	1	2	3	4	5	6	7	8
01	4156	2836	2051	2795	2899	2104	2257	2136	2952	5214	3651	2254	2995	2491	4118	2362	2265	2569
02	7088	4780	4720	6190	8894	6025	4895	3906	4048	E	7501	4341	3902	5058	5597	E	6443	6861
03	3965	2580	2725	5476	2059	3058	3847	2784	2803	4540	2554	4264	4558	3723	11204	8533	6887	3360
04	10022	3671	3418	2428	3706	2395	2704	5896	3091	4433	3609	2728	2358	8119	4601	2674	2530	4526
05	6177	5031	5113	4302	6017	4442	5805	5863	6183	5243	4813	7159	6670	6600	4928	6111	7014	5359
06	3136	2726	4533	2927	3159	2410	3744	3736	3838	3442	E	2209	2616	3582	2869	3857	3748	4536
07	3576	2207	2286	2550	2488	2396	2342	2206	2116	3948	3908	3120	2790	4798	3790	1908	2316	3344
08	6979	2608	2224	2324	2168	2302	2053	1900	3208	2637	2135	2434	2425	M	4416	2237	2328	2657
09	2461	1987	1793	1801	6503	3576	1989	2693	2861	8049	4333	2089	4642	M	4032	2553	3194	6011
010	5252	2600	2573	2770	3293	2861	3150	1909	3292	2546	2526	2157	2148	2786	3801	2443	2204	2427
011	1748	1831	1619	1687	2120	1696	1770	1908	1842	2262	1836	2328	1800	2240	1794	1927	1921	1860
012	3233	2224	1851	2218	2444	3898	1969	2222	2153	4557	2746	2810	2672	4176	3564	3504	1989	3106
013	2454	4914	4688	E	5894	5044	5553	4453	2720	4775	7858	3397	5702	M	5585	3634	5646	9610
014	2301	1748	1672	1962	1998	1894	1690	1888	2478	2322	2107	1990	1938	2360	2499	2131	2009	2537
015	2511	2901	1659	1749	3925	2036	2085	1701	1820	3618	3128	2880	2214	2661	2334	1884	2146	2807
016	1865	1747	1603	2128	1783	2227	1877	1935	2186	2027	2929	2113	2822	E	2347	2906	E	3453
017	3038	1504	1257	3127	1892	3724	1779	1759	3440	11900	2656	1724	1701	2444	2908	6577	3709	2353
018	3257	2135	2960	2658	3258	2894	2167	2478	2674	2430	2564	3313	2798	2605	2337	2724	3523	3889

M = No response

E = Response time not recorded

TABLE VI-14

Time Taken to Respond to the Warning Shout (milliseconds)

Office Employees Wearing Earmuffs

Subject	Background Sound Level 75dB(A) Stimulus Position									Background Sound Level 95dB(A) Stimulus Position								
	0	1	2	3	4	5	6	7	8	0	1	2	3	4	5	6	7	8
01	2153	2121	2546	2186	2838	3015	2246	2130	2696	2500	2342	2272	2060	2145	2087	2030	4260	2277
02	8500	5538	5541	4275	9187	4790	4523	4874	7486	4508	4913	4237	5160	7091	3843	7322	5155	6799
03	2252	2709	2124	2451	3104	2862	2656	2165	3178	4815	2530	4769	12650	1730	4767	4732	8184	3655
04	11148	4174	2569	2893	3825	3902	3448	2750	2906	5227	3874	2725	3210	6880	3306	3531	3514	4320
05	5495	5051	2749	4871	128	2231	5818	4144	4651	4236	5796	3085	6568	5752	4359	4762	5090	4382
06	3332	3608	4045	2318	3217	2722	2519	2899	2975	3301	2943	3073	4499	5321	5188	2627	15919	E
07	2751	3360	2780	2659	3323	2198	2098	2052	2906	3772	E	2360	2896	2870	2608	2507	3109	2520
08	2155	1972	1932	2351	2041	1796	1701	1725	2889	2213	1935	1975	2334	2818	2414	2365	1915	2006
09	2543	2288	2222	2352	5183	11045	2540	2874	2470	7889	4821	2403	3853	5064	7539	6236	7996	5039
010	4007	2427	3667	2846	2793	3008	3174	2570	3076	2617	2997	2385	2960	M	3143	4774	2568	5079
011	2068	1899	2749	2044	1960	1927	2132	2104	2101	1837	2348	2214	2242	2345	1753	2027	2174	2332
012	3129	3869	4179	6135	4560	2071	2018	2094	2111	7034	5241	5929	2745	10919	2905	6190	5229	4143
013	3190	2829	4631	7441	3804	7823	6583	3550	3020	6454	2944	4063	E	7234	5320	4764	4854	4126
014	2103	1927	2019	1723	2365	2253	1872	1768	2671	2241	2035	2040	1937	3517	2251	2340	2311	2486
015	2331	2306	2287	2120	2425	3024	2726	2019	2821	4159	2634	1965	3623	M	4120	2690	3432	2695
016	2303	2902	1814	2129	1588	2397	1961	1902	1741	2563	2016	1911	2041	3221	3764	2792	3051	M
017	4745	3064	5220	2151	9810	4018	3876	2649	4228	2803	5911	3972	6776	6664	4246	2912	5353	4259
018	2674	3301	3357	2775	2278	2673	4133	1954	1836	2370	2508	2643	2928	M	3228	2269	2127	2882

M = No response

E = Response time not recorded

APPENDIX VII

APPENDIX VII

VISUAL CONTROL EXPERIMENT FOR FOUNDRY LOCALISATION STUDIES

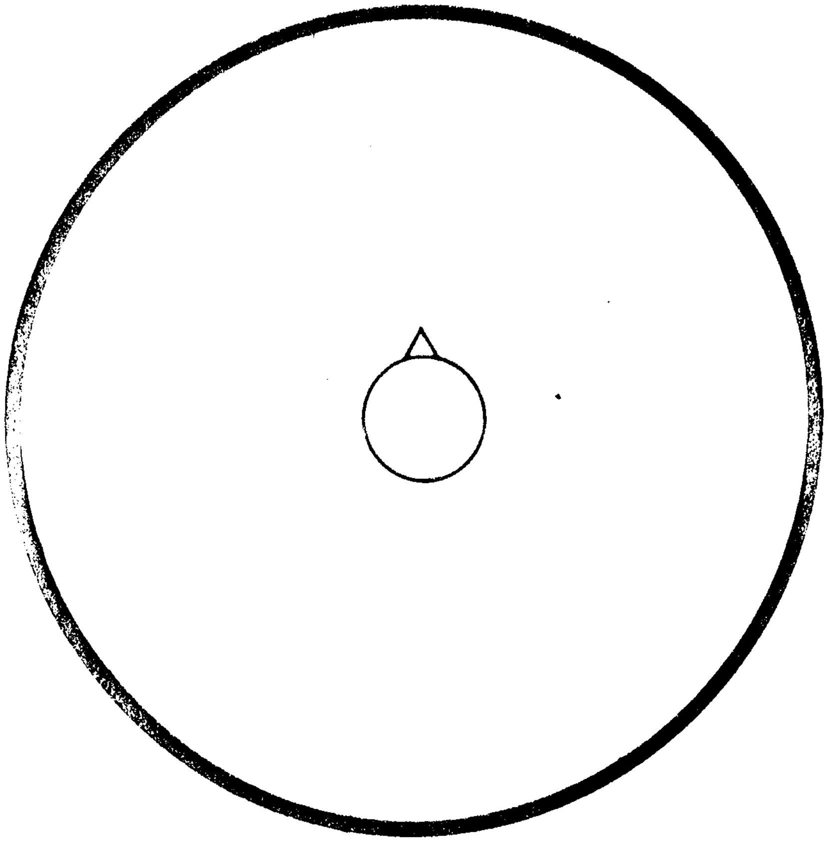
The response method used during the studies of localisation of warning shouts at a foundry (Chapter 4) allowed the subject a free choice of response direction, whereas previous studies of localisation with hearing protectors presented subjects with finite sets of discrete response directions from which to choose.

During the foundry localisation studies, subjects responded by marking the position from which they thought a shout had originated;with a ballpoint pen on a response diagram as in Figure VII-I. Although the literature of localisation experimentation contains reports of many varieties of response method, this type of response method has not been described previously.

A visual control experiment was therefore incorporated in the foundry experiments to explore the nature of errors and bias inherent in the response method. However, it must be remembered that there are distinct disadvantages in using visual stimuli to explore the errors associated with the response method used during the auditory localisation study. The translation onto response diagrams of the positions ascribed to the stimuli by the subjects might be accomplished by fundamentally different processes for visual and auditory

FIGURE VII-1

Response Diagram - The Subject Was Asked to Mark the Circle at the Position from which He Thought the Light had originated



stimuli.

However, the use of a visual stimulus which the subject could see, and therefore respond to easily, did provide a method of discovering more about the potential sources of bias and errors associated with the response method.

Experiment

The visual control tests took place at the same experimental sessions as the localisation of warning shout tests. The visual control tests were completed by the subject subsequent to the completion of the localisation tests described in Chapter 4.

Subjects:

Twenty-one fettlers and seventeen office employees completed the experiment. Demographic details for the subjects have been described in Chapter 4; one office employee (02) who participated in the warning shout tests did not provide results for the visual control tests.

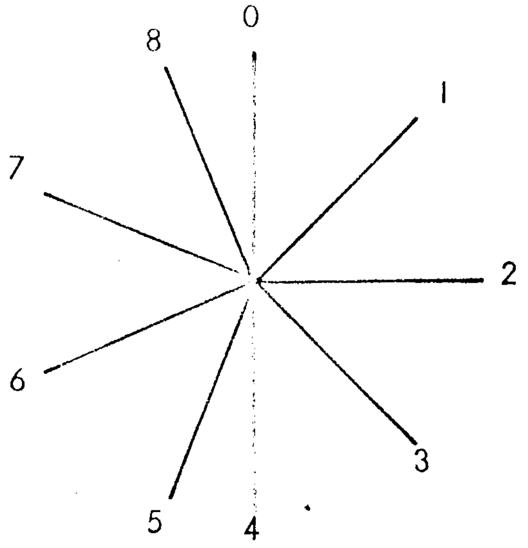
Apparatus:

The subject was seated at a table at the centre of a semi-anechoic chamber and surrounded by a black curtain at a radius of 1.2 m. Opaque white screens (width 2 cm., height 5 cm.) were set into the black curtain at the same height as the subject's head at the positions shown in Figure VII-2.

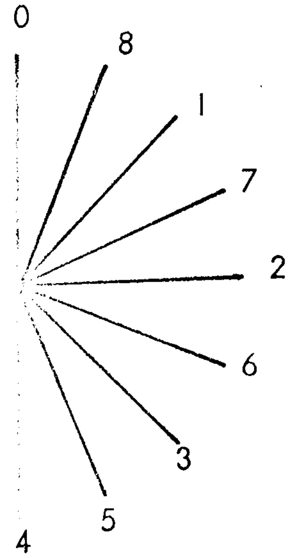
FIGURE VII-2

Directions from Which Visual Stimuli were Presented during the Visual Control Experiment

Actual Directions



Angular Directions following transposition to the right of the median plane of all stimulus directions that were actually to the left of the median plane.



The small white screens could be illuminated from outside the black curtain in any order.

A pad of response diagrams was clipped to the table in front of the subject.

The only lighting in the semi-anechoic chamber during the tests came from the illuminated opaque stimulus screen and the pool of light directed from above the subject onto the response diagrams. A white ribbon (4 cm. wide) pinned vertically to the black curtain directly in front of the subject was provided as a reference.

Procedure:

The experimental procedures and temporal pattern of the tests have been described in detail in Chapter 4 and Figure 19. During the visual control tests, the subjects were asked to mark the position of the nine sources on the response diagram and then to turn to a new response diagram.

The order of presentation of the visual stimuli was randomised separately for each subject.

The small opaque screens were illuminated until the subject had responded and turned to a new response diagram.

The subject had to turn his head, or the upper part of his body, to locate stimuli from positions 3,4,5 and 6 in Figure VII-2.

Analysis of Results of Visual Control Experiment

The experiment followed a split-plot factorial design* with two factors (subject group and stimulus direction) with repeated measures of one factor (stimulus direction). The experiment was designed to have equal numbers of subjects in both office employee and fettler subject groups. Twenty-one fettlers participated in the experiments but four of the office employees were not able to take part. An unweighted-means solution had to be incorporated into the analysis of variance because the subject groups were of unequal size (Kirk, 1968). Another problem encountered during the analysis was that two subjects - one office employee and one fettler - provided one response each which could not be coded because they had marked the response diagram in two places. A procedure, described by Kirk (1968), which is applicable when only one response in a block is missing, was used to estimate the two missing responses.

* In the nomenclature of Kirk (1968) the experiment followed a SPF2.9 design.

Angular Response Error

The angular errors made by each subject when responding to the visual stimuli are given in Table VII-1 for the fettlers and in Table VII-2 for the office employees. The response errors for each of the nine stimulus directions are

TABLE VII-1

ANGULAR RESPONSE ERROR IN DEGREES MADE BY EACH OF THE FETTLERS FOR EACH OF THE NINE POSITIONS OF THE VISUAL STIMULUS

Subject	Stimulus position								
	0	1	2	3	4	5	6	7	8
F1	0	3f	1f	2r	2f	5f	18r	5r	8r
F2	1r	0	0	9r	13f	13*	32r	9f	1r
F3	1r	11r	6f	4r	0	0	18r	6f	3f
F4	0	1r	2f	2f	5f	10f	18r	16r	23r
F5	1r	2f	2f	1f	4f	2f	2r	5r	3f
F6	1r	8f	1r	6r	20f	2f	8r	4f	9r
F7	1r	13f	0	4f	1f	22r	17f	6f	0
F8	6r	9f	0	5r	4f	15r	14r	11r	10r
F9	3r	7f	3f	18f	0	25r	3r	8f	1r
F10	1r	7r	12f	16r	39f	53f	17f	22f	3f
F11	0	0	0	14r	1f	8f	21f	10f	7r
F12	2r	3r	22f	26f	7f	14f	3r	7r	16f
F13	1r	12f	3f	0	2f	6f	1r	10f	4r
F14	0	9f	6f	3f	7f	6f	0	5r	26r
F15	2r	11f	22f	35f	6f	13r	13r	22f	8r
F16	1r	11f	0	2f	18f	20r	11r	6f	5r
F17	0	13f	0	6r	8f	12r	9f	0	13r
F18	2r	7f	1f	10r	4f	0	7f	4f	4f
F19	3r	5r	8r	12r	10f	16f	5r	10r	5r
F20	2r	12r	2r	0	7f	12f	15r	13r	14r
F21	0	4f	2f	1f	5f	4f	24f	12f	5r
Mean response error	1.3	7.0	4.4	8.4	7.8	12.3	12.2	9.1	8.0
Variance	2.0	19.1	43.7	83.9	80.2	136.8	71.2	31.5	48.8
Mean Response Direction	1.3r	3.3f	3.4f	0.4f	7.8f	1.5f	5.4r	2.2f	6.8r

* estimated value

f = response forward of stimulus

r = response to the rear of stimulus

TABLE VII-2

ANGULAR RESPONSE ERROR IN DEGREES MADE BY EACH OF THE OFFICE EMPLOYEES FOR EACH OF THE NINE POSITIONS OF THE VISUAL STIMULUS

Subject	Stimulus position								
	0	1	2	3	4	5	6	7	8
01	9r	8f	8f	5r	1f	24f	11r	7r	23r
02	-	-	-	-	-	-	-	-	-
03	0	1r	2r	13r	3f	1f	8r	3r	2r
04	0	1r	2f	13r	15f	3f	9r	0	9r
05	1r	1r	5f	4f	3f	11r	9f	2f	10r
06	0	6r	2f	0	7f	24f	1r	4f	5r
07	5r	9f	1r	5f	0	13f	4r	21f	1r
08	1r	4f	0	6r	0	3r	22r	9r	25r
09	0	1f	3r	11r	4f	3r	15f	22f	4f
010	0	0	0	11f	1f	6f	3f	4f	13r
011	3r	8r	7f	3f	35f	28f	8r	11r	23r
012	0	14f	4f	11f	5f	7f	13f	5f	13r
013	1r	8f	5f	14r	20f	16r	33r	15r	1f
014	0	10f	8f	14f	6f	17f	4r	10f	4f
015	1r	3r	1r	14f	6f	3r	3f	5f	15r
016	7r	0	9f	4r	3f	31f	12*	2r	16r
017	0	4f	18f	25f	3f	17r	24f	25f	6r
018	4r	12f	8f	2r	5f	13f	9r	22f	10r
Mean response error	1.9	5.3	4.9	9.2	6.9	12.9	11.0	9.8	10.6
Variance	7.7	19.8	20.6	40.1	79.4	91.6	71.9	66.8	61.0
Mean response direction	1.9r	2.9f	4.1f	1.2f	6.9f	6.7f	2.5r	4.3f	10.1r

* estimated value
f = response forward of stimulus
r = response to the rear of stimulus

accompanied by an indication of the position of the response relative to the stimulus position (response forward of stimulus:f; response to the rear of the stimulus: r).

Also included in Tables VII-I and VII-2 are: mean angular response errors for each stimulus direction; mean response position for each stimulus direction; and estimates of the variance within the subject groups.

The mean response errors for each stimulus position and mean response positions for the subject groups combined are listed by stimulus position in Table VII-3. The mean response errors for each of the stimulus positions are illustrated in Figure VII-3. The mean response positions are illustrated in Figure VII-4.

As can be seen from Table VII-I and Table VII-2, there appears to be a marked heterogeneity of error variance for both the fettler and office employee subject groups. A Hartley Fmax test (Kirk, 1968) indicated the presence of significant heterogeneity of error variance amongst the nine stimulus positions.

(Hartley's Fmax test for homogeneity of error variance: fettler subject group - error variance x nine stimulus positions; Fmax = 67.4, df = 9 and 20, $p < 0.01$; office employee group - error variance x nine stimulus positions, Fmax = 11.8, df = 9 and 16, $p < 0.01$)

TABLE VII-3

MEAN RESPONSE ERROR AND MEAN RESPONSE POSITION FOR THE NINE POSITIONS OF THE VISUAL STIMULUS: FETTLER AND OFFICE EMPLOYEE SUBJECT GROUPS COMBINED

Stimulus position	0	1	2	3	4	5	6	7	8
Mean response position degrees forward (f) or rearward (r) of stimulus	1.6r	3.1f	3.7f	0.8f	7.4f	3.8f	4.1r	3.1f	8.3r
Mean response error degrees	1.6	6.2	4.6	8.8	7.4	12.6	11.7	9.4	9.2

Note: The mean response errors and variances for the subject groups combined were used to calculate the maximum response errors likely to occur at positions 0 and 4 for 95 percent of responses. It was calculated that five percent of all responses to stimuli from directly in front of the subjects could be expected to exceed an error of 3.5 degrees; similarly, five percent of responses to stimuli from directly behind could be expected to exceed an error of 14.5 degrees.

FIGURE VII-3

Mean Response Error for Each of the Nine Positions of the Visual Stimulus: Fettler and Office Employee Groups Combined

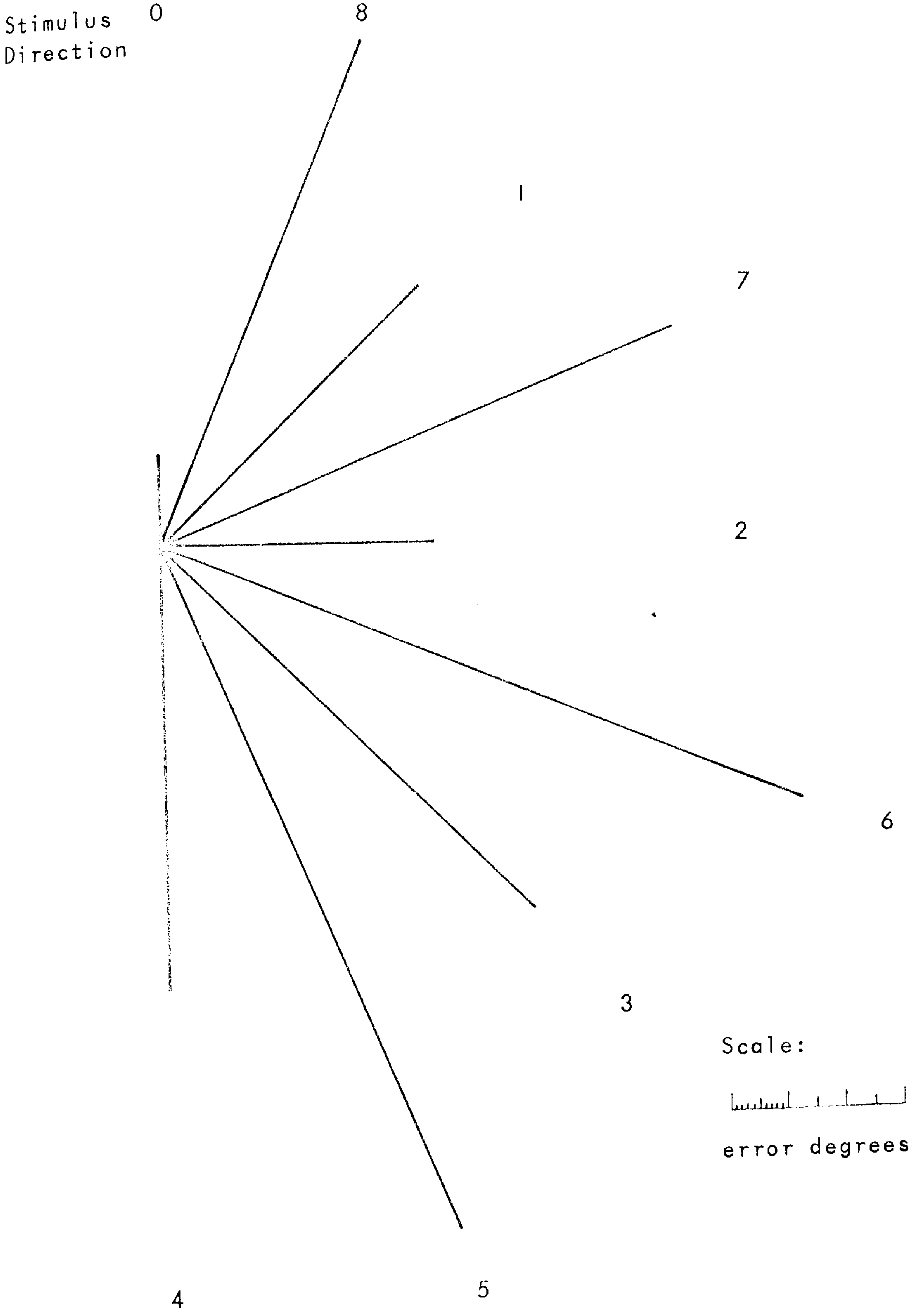
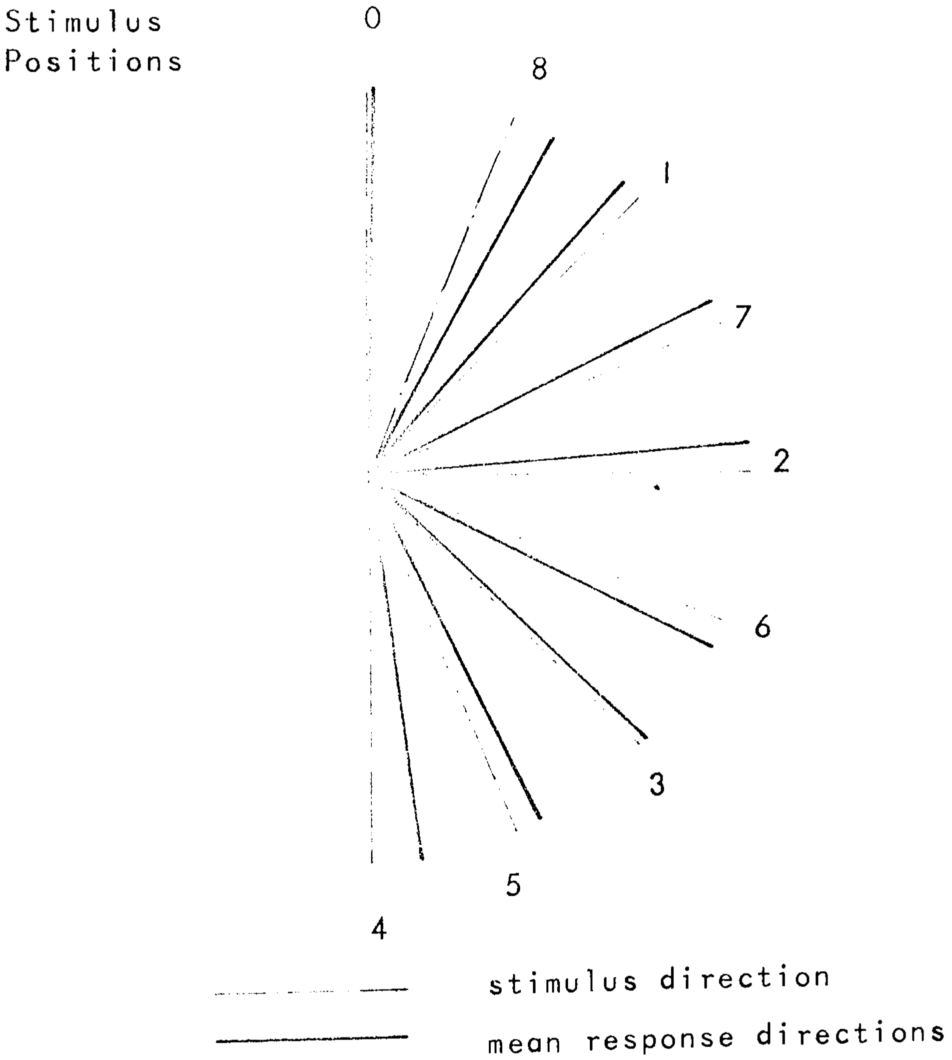


FIGURE VII-4

Mean Response Positions Relative to the Nine Visual Stimulus Positions: Fettler and Office Employee Subject Groups Combined



Subjects could locate stimuli from positions 0,1,7 and 8 in front of them without moving their bodies, but the locating of stimuli from other positions could not be achieved without some movement of the head or body. I thought that this might have accounted for the heterogeneity. However, significant heterogeneity of error variance was demonstrable when the stimuli, for which the subjects would have had to turn their heads or bodies, were removed from the analysis.

(Hartley's Fmax test for homogeneity of error variance: fettler subject group - error variance x four stimulus positions (0,1,7 and 8); Fmax = 24.3, df = 4 and 20, $p < 0.01$; office employee group - error variance x four stimulus position (0,1,7 and 8); Fmax = 8.7, df = 4 and 16, $p < 0.01$)

The unweighted-means solution for the analysis of variance is presented in Table VII-4. Geisser-Greenhouse conservative F tests have been used in the analysis of variance because of the presence of significant error-variance heterogeneity (Kirk, 1968).

Differences in response error between the two subjects groups were not found to be significant. Nor was any significant interaction between stimulus position and subject group identified. However, the position of the stimulus was found to significantly affect the angular response error.

TABLE VII-4

ANALYSIS OF VARIANCE SUMMARY FOR THE SPLIT-PLOT TWO FACTOR (SUBJECT GROUP X STIMULUS POSITION) VISUAL CONTROL EXPERIMENT

	Source	Sum of Squares	Degrees of Freedom	Mean Squares	F Ratio	F
1	Subject group	4.0	1	4.0	1/2	0.04
2	Subjects within groups	3831.7	36	106.4		
3	Stimulus position	3444.2	8	430.5	3/5	8.95*
4	Subject group x stimulus position	121.8	8	15.2	4/5	0.32
5	Stimulus position x subjects within groups	13856.9	288	48.1		
6	Stimulus position x subjects within groups corrected for missing responses	13856.9	286	48.5		

* Conservative F ratio = 8.89 with df = 1, 35.7, $p < 0.01$.
Unweighted-means solution with subject group and stimulus position fixed effects and subjects within groups random effects (Kirk, 1968).

(Angular response error made by office and fettler subjects: Geisser-Greenhouse conservative $F = 8.89$, df = 1 and 36, $p < 0.01$).

Scheffe's method was used to make multiple comparisons between the mean response errors for the different types of stimulus positions.

The mean angular response errors for stimulus positions 1 and 3 (the quadrant bisectors) did not differ significantly from the angular response error for position 5,6,7 and 8 (positions 22.5 degrees from quadrant bisectors).

(Scheffe's comparison of mean angular response error: Stimulus positions 1 and 3 with stimulus positions 5,6,7 and 8; $F = 10.8$, df = 8 and 286, $p \sim 0.25$; or with conservative test, df = 1 and 36, $p > 0.25$)

Similarly, the mean response error for the stimulus position 2 (directly to the right of the subjects) was not significantly less than the error made when the stimulus was presented at positions 1 and 3 (the quadrant bisectors).

(Scheffe's comparison of mean angular response error: Stimulus positions 1 and 3 with stimulus position 2; $F = 4.3$, df = 8 and 286 (df = 1 and 36 for conservative test), $p > 0.25$)

However, visual stimuli from directly ahead of the subjects produced significantly less angular response error than other stimulus positions.

(Sheffe's comparison of mean angular response error: Stimulus position 0 with stimulus positions 1,2,3,4,5,6,7 and 8; $F = 35.8$, df = 8 and 286, $p < 0.01$, or with conservative test, df = 1 and 36, $p < 0.05$)

Similarly, visual stimuli from positions 0,2 and 4 were more accurately located than the stimuli from positions 5,6, 7 and 8.

(Sheffe's comparison of mean angular response error: Stimulus positions 0,2 and 4 with stimulus positions 5,6,7 and 8; $F = 57.7$, df= 8 and 286, $p < 0.01$, or with conservative test, df = 1 and 36, $p < 0.05$)

Stimuli from forward of the subjects were not necessarily located significantly more accurately than stimuli to the rear of the subjects.

(Sheffe's comparison of mean angular response error: Stimulus positions 0,8,1 and 7 with stimulus positions 6,3,5 and 4; $F = 19.1$, df = 8 and 286, $p \sim 0.05$, or with conservative test, df = 1 and 36, $p > 0.25$)

Further comparisons between pairs of stimulus positions were analysed by Tukey's method (Kirk, 1968); the comparisons have been summarised in Table VII-5; a significance level of p = 0.05 has been adopted.

Summary

The analyses clearly indicated the presence of significant error variance heterogeneity in the angular responses for the visual stimuli from different directions. Error variance was heterogeneous for stimuli presented from forward of the subjects, which suggested that the heterogeneity could not have been caused solely by the differences between the task of responding to a stimulus in front and turning the head or body to locate a stimulus from behind.

No significant difference was found between the accuracy of fettlers and office employees.

However, the position of the visual stimulus was found to affect the accuracy of the subject's responses significantly.

Stimuli from positions directly in front, directly behind, and directly to the side of the subjects produced significantly more accurate responses than positions 22.5 degrees from the quadrant disectors (ie. positions 5,6,7 and 8).

TABLE VII-5

SUMMARY OF COMPARISONS BETWEEN MEAN ANGULAR RESPONSE ERROR FOR PAIRS OF VISUAL STIMULUS POSITIONS BY TUKEY'S METHOD

Stimulus Positions	0	1	2	3	4	5	6	7	8
0				S	S	S	S	S	S
1						S	S		
2						S	S		
3	S								
4	S					S			
5	S	S	S		S				
6	S	S	S						
7	S								
8	S								

S = difference significant at p 0.05

Conclusions

The combination of visual task and response method used in the visual control experiment resulted in significant error variance heterogeneity. The tasks of locating visual stimuli forward of the subject and to the rear of the subject were different (ie. the subject had to move his head and body to locate some of the stimuli from behind), but this difference did not fully account for the error variance heterogeneity.

The heterogeneity may not be a feature inherent in the response method, but it would, however, be unwise to assume that homogeneity of error variance would result from the use of the response method in auditory localisation studies.

Similarly, the variation in response error with stimulus position may not be an inherent feature of the response method. However, if the response method is used for localisation experiments, the marked variation in accuracy with stimulus position must severely reduce the confidence with which conclusions could be drawn about the variation in localisation ability with direction.

APPENDIX VIII

APPENDIX VIII

FURTHER RESEARCH

The research presented in this thesis has highlighted the need for further research in the following areas:

1. Protection provided by hearing protectors in practice in industry

1.1 With what degree of accuracy do laboratory measurements of hearing protector attenuation predict the attenuation provided for the industrial users of the hearing protectors?

The method of measurement of attenuation provided by hearing protectors at threshold (British Standards Institution, 1974) could be used to measure attenuation provided by a commonly used type of earplug and a commonly used type of earmuff as used in industry. Small groups of users (15 subjects) from different user populations (eg. women, and industrial workers from different ethnic groups) could be asked to fit the hearing protectors as they would in their normal work and then have attenuation tested by the British Standard method. The results from these tests could be compared with data from manufacturers.

1.2 With what degree of accuracy does the method of estimating the reduction in A-weighted sound level provided by hearing protectors (ie. attenuation data for correctly fitted new hearing protectors applied to octave-band sound levels) predict the protection (reduction in ECSL) provided by the hearing protectors in practice in industry?

Small microphones positioned at the subjects' ears and connected to integrating noise dosemeters might provide a method of estimating the reductions in ECSL provided by earmuffs. This method might be adequate to explore the effects of: earmuff fitting procedures; the removal of earmuffs for part of an exposure; the deterioration of hearing protectors after they have been in use for some time.

1.3 Which centile estimates from attenuation data should be used in the selection of hearing protectors?

My preliminary work on the reduction in risk of occupational deafness provided by hearing protectors should be extended by computer modelling with hearing level criteria other than $25\mathrm{dBHL}_{\overline{0.512}}$ and with long-term audiometric studies with small, closely supervised populations of hearing protector users.

2. <u>Effects of hearing protectors on the safety of the users</u>

2.1 What factors govern the perception of warning sounds and indicator sounds by normal-hearing and hearingimpaired wearers of hearing protectors?

It will be necessary to develop a system for estimating the effects of hearing protectors (advantageous or disadvantageous) on the perception and monitoring of sounds from: analyses of the spectral and temporal composition of the background noise and the warning or indicator sounds; the attenuation data for the hearing protector; and the hearing levels of the user.

2.2 Can hearing protectors affect the user's sense of balance?

I continually receive reports that wearers of hearing protectors complain that the protectors upset their sense of balance. If hearing protectors do not affect balance, then an explanation must be found for the apparent effect - perhaps in terms of the feeling of isolation induced by the hearing protectors, or the effect which they have on directional hearing.

2.3 Are the voice levels of industrial users of hearing protectors lowered by the wearing of the protectors?

2.4 Can people be trained to use the same voice level when they wear protectors as they would use if they were not wearing protectors?

2.5 Will the wearing of hearing protectors reduce the sound level at which a worker will shout a warning to a workmate?

The reduction in voice level occasioned by the wearing of hearing protectors was discussed in Chapter 5, but research has yet to show that industrial users do not naturally overcome the effect and that new users cannot be trained to maintain high voice levels. When people shout warnings, they may not monitor the voice level by audition. They may use some other physiological monitoring system, or use the maximum capacity of their lungs - therefore hearing protectors may not reduce the sound level of their shouted warning.

2.6 Are hearing protectors of high attenuation which do not cover the pinnae likely to affect localisation less than earmuffs of the same attenuation which do cover the pinnae?

The recent development of earplugs made from high hysteresis polyurethane foam would provide a suitable high attenuation earplug for comparison with a light-weight earmuff of similar sound attenuating properties.

2.7 Do hearing protectors reduce the wearer's ability to make use of binaural release from masking?

Hearing protectors have been shown to affect localisation of stimuli in high background noise levels. Green and Henning (1969), in their review of research in sound localisation and binaural hearing, suggested if a signal and noise are not localised differently, then probably there will be no binaural release from masking. Some authors have presented results from lateralisation studies which indicate that the processes of binaural release from masking and localisation may be at least partially different (eg. Jeffress, Blodgett and Deatherage, 1952; Egan and Benson, 1966). Hearing protectors might have a detrimental effect on binaural release from masking which could further explain complaints of feeling isolated and the resistance to wear hearing protectors.

3. Comfort and acceptability of hearing protectors

3.1 Would a low attenuation hearing protector be more acceptable to a user than an equally comfortable high attenuation protector?

3.2 Which are the important design parameters governing the comfort, acceptability and degree of usage of hearing protectors?

My research has highlighted the need to achieve a very high degree of usage of hearing protectors. Selectors and designers of hearing protectors should be provided with guidance to ensure that more comfortable and acceptable protectors are designed and selected for use in industry.

APPENDIX IX

FIGURES AND TABLES TO VOLUME I

TABLES AND FIGURES CHAPTER TWO

Tables 1 - 4

Figures 1 - 10

FIGURE I

Percentages of an Otologically Normal Population Likely to Exceed the Hearing Level Criteria Following Exposure to Noise for a Working Lifetime (49 years, 50 weeks per year, 5 days per week, 8 hours per day) to Sound Levels in the Range 80dB(A) to 120dB(A)

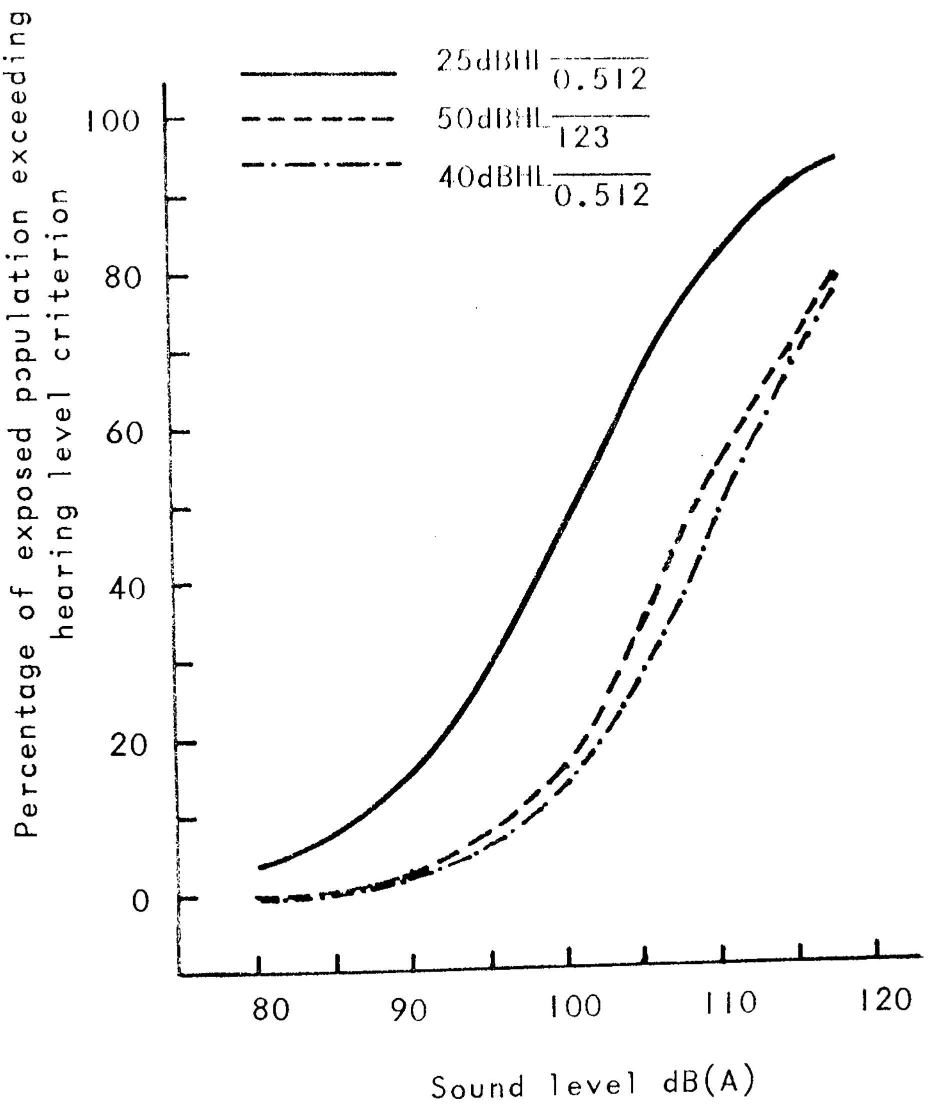


TABLE I

The Residual Risks from a Working Lifetime of Exposure to 90dB(A)

Percentage of otologically normal population exceeding $25\text{dBHL}_{\overline{0.512}}$ (1)	16
Percentage of otologically normal population exceeding $40\text{dBHL}_{\overline{0.512}}$ (1)	2
Percentage of unselected population exceeding $25\text{dBHL}_{\overline{0.512}}$ (2)	65
Percentage of exposed population exceeding an arbitary standard of handicap based upon symptoms (3)	1
Percentage of exposed otologically normal population exceeding $50\text{dBHL}_{\overline{0.512}}$ (1)	4

(1) Derived from the tables compiled by Robinson and Shipton (1973); the working lifetime has been assumed to be of 49 years' duration, starting in the seventeenth year; assumed symmetrical hearing losses.

(2) Working lifetime of 45 years starting in the nineteenth year (ISO R1999, 1971).

(3) Working lifetime of 30 years (British Occupational Hygiene Society, 1971).

FIGURE 2

Flow Chart of Computer Model for Estimating the Residual Risks for a Population Wearing Hearing Protectors

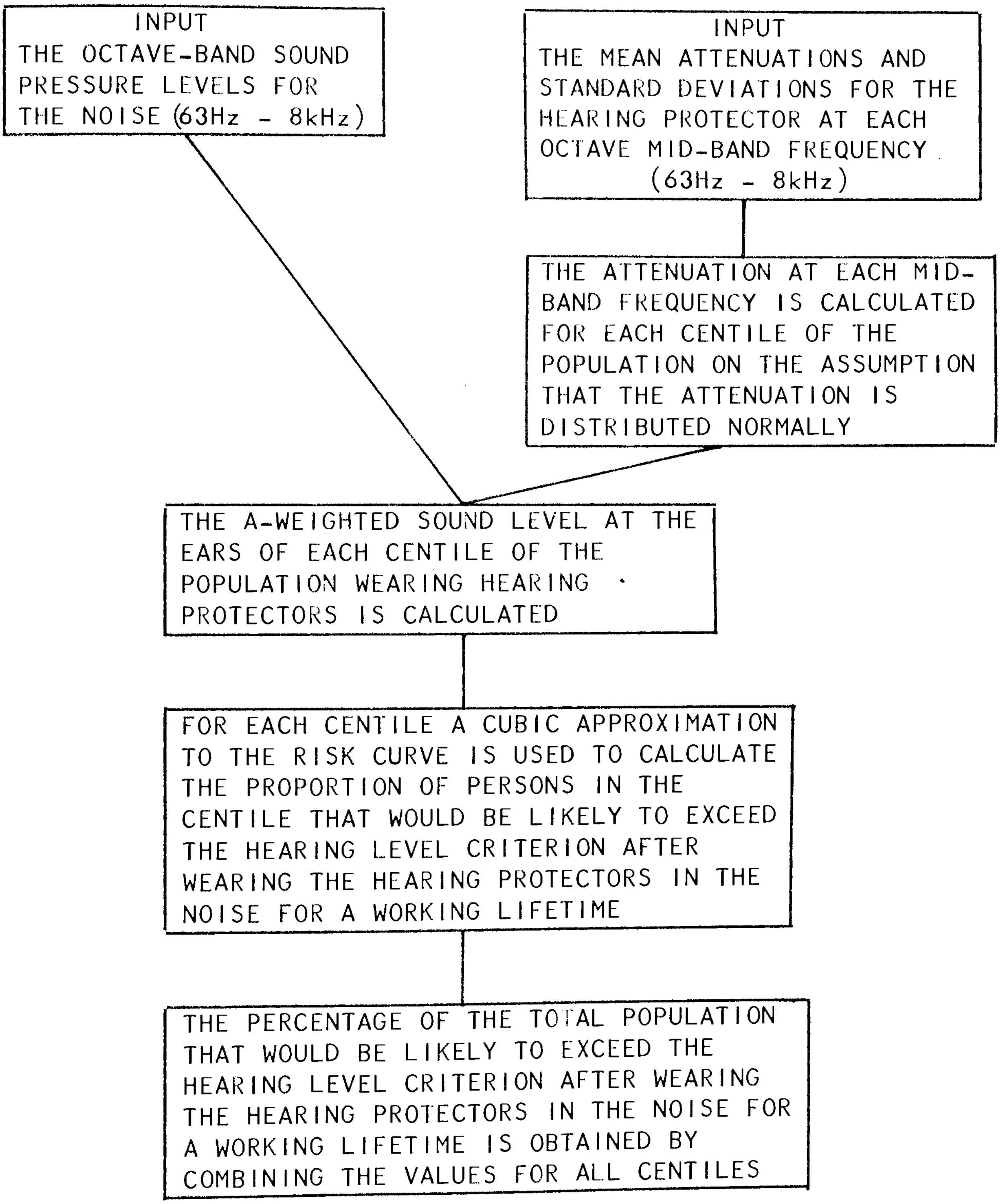


FIGURE 3

Residual Risk of Exceeding $25\text{dBHL}_{\overline{0.512}}$ for Hearing Protector Users Exposed for a Working Lifetime (49 years, 50 weeks per year, 40 hours per week) to Noise Levels in the range of 85 dB(A) to 120dB(A); for Hearing Protectors Providing Mean Reductions in Sound Levels 5dB(A) to 35dB(A) with Standard Deviation of 5dB(A)

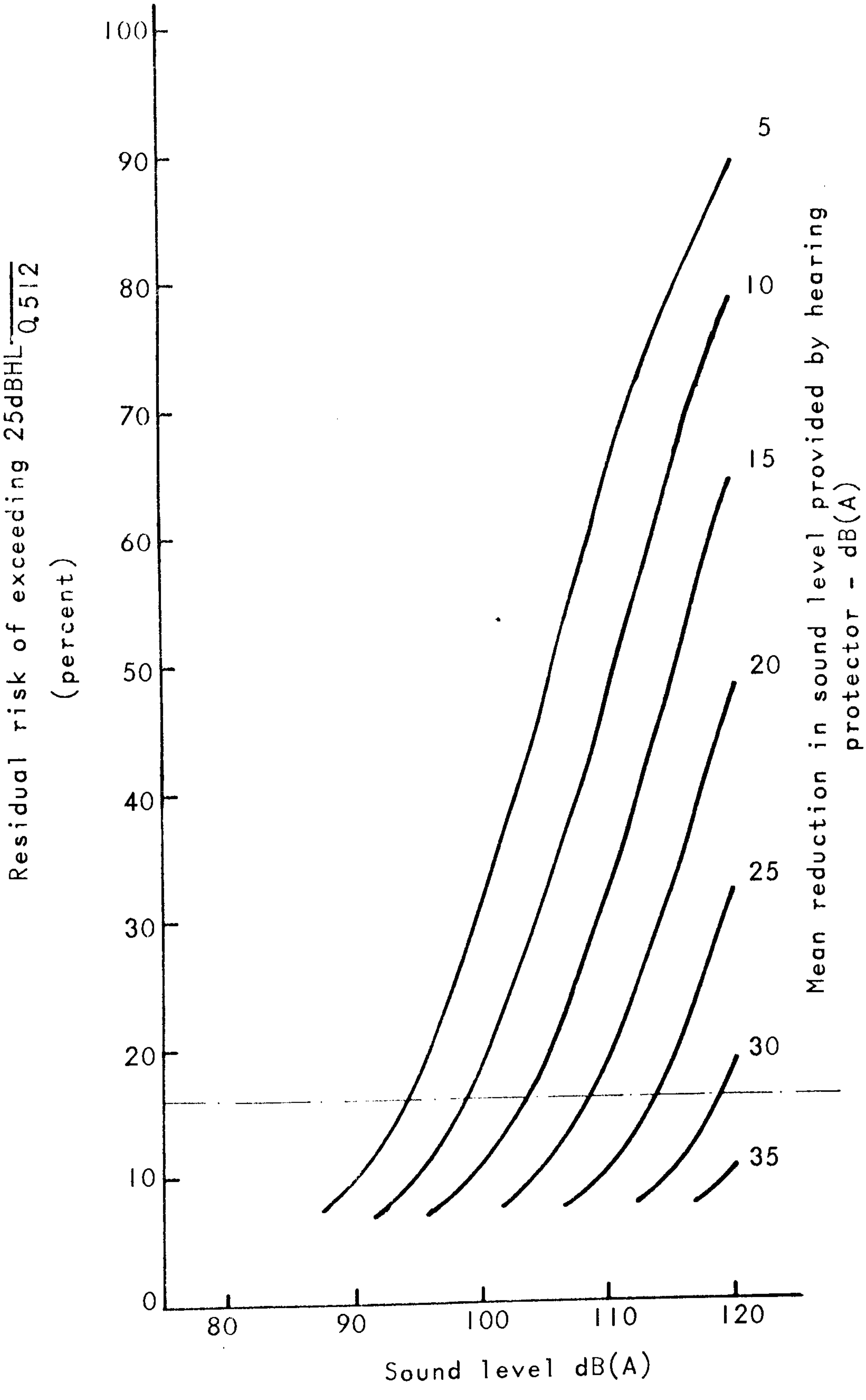


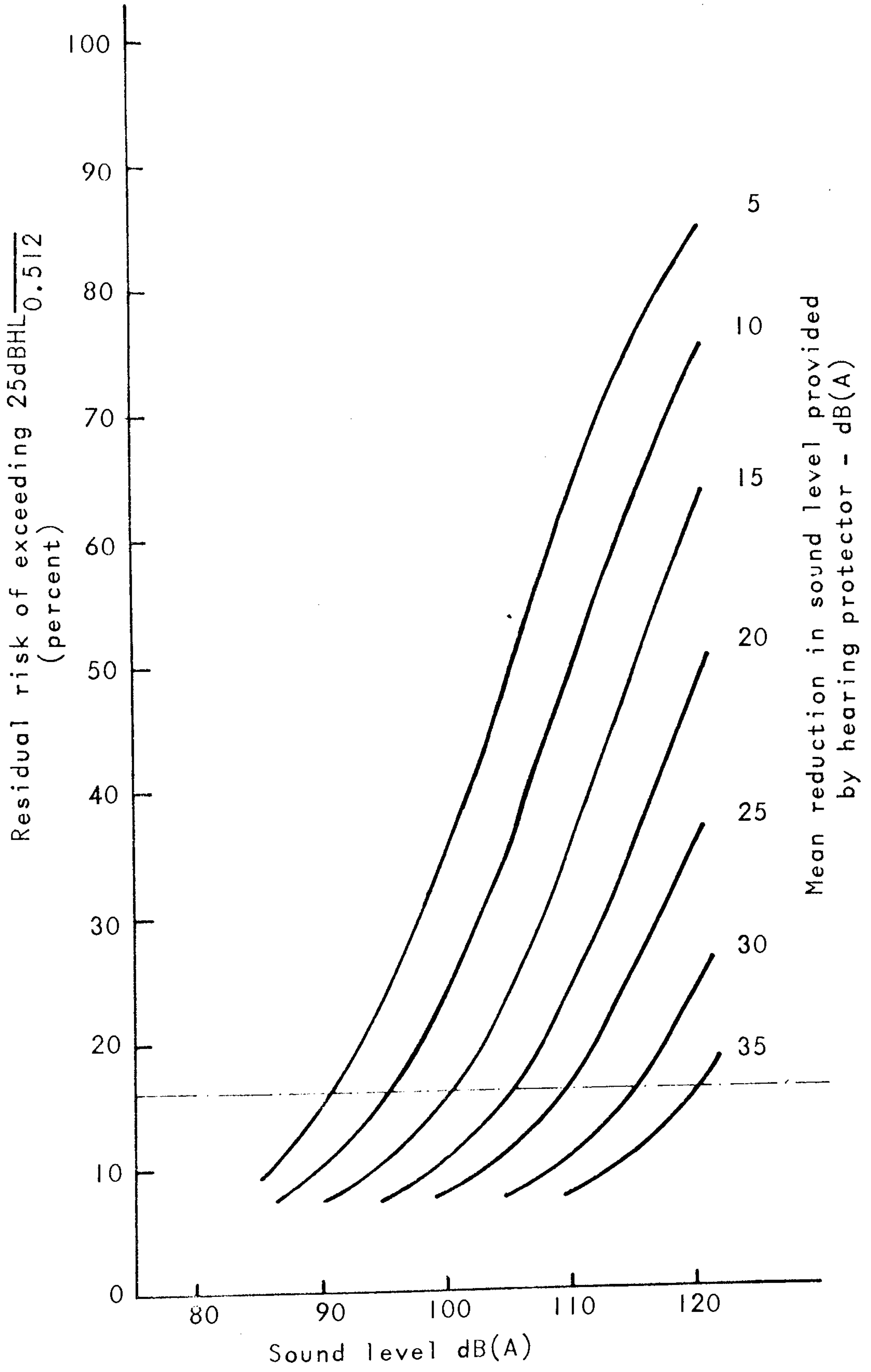
TABLE 2

Residual Risk of Exceeding 25dBHL$_{\overline{0.512}}$ for Wearers of Hearing Protectors Selected According to Various Criteria

Selection Criteria	Sound Level dB(A)		
	95	105	120
Mean attenuation set to 90dB(A) standard deviation = 5dB(A)	19	19	19
Lower quartile attenuation set to 90dB(A) standard deviation = 5dB(A)	12	12	12
Mean-standard deviation set to 90dB(A) standard deviation = 5dB(A)	10	10	10
Mean - 1.5 x standard deviation set to 90dB(A) standard deviation = 5dB(A)	8	8	8
Mean attenuation set to 90dB(A) standard deviation = 10dB(A)	23	24	24
Lower quartile attenuation set to 90dB(A) standard deviation = 10dB(A)	13	14	14
Mean-standard deviation set to 90dB(A) standard deviation = 10dB(A)	10	10	10
Mean - 1.5 x standard deviation set to 90dB(A) standard deviation = 10dB(A)	8	8	8

FIGURE 4

Residual Risk of Exceeding $25dBHL_{\overline{0.512}}$ for Hearing Protector Users Exposed for a Working Lifetime (49 years, 50 weeks per years, 40 hours per week) to Noise Levels in the Range 85dB(A) to 120dB(A); for Hearing Protectors Providing Mean Reductions in Sound Level 5dB(A) to 35dB(A) with Standard Deviation of 10dB(A)



SDS = 10dB

FIGURE 5

The Maximum Protection Provided by Hearing Protector as a Function of the Percentage of exposure duration that Hearing Protector is Worn: It is Assumed that no Noise is Immitted whilst the Protector is Worn

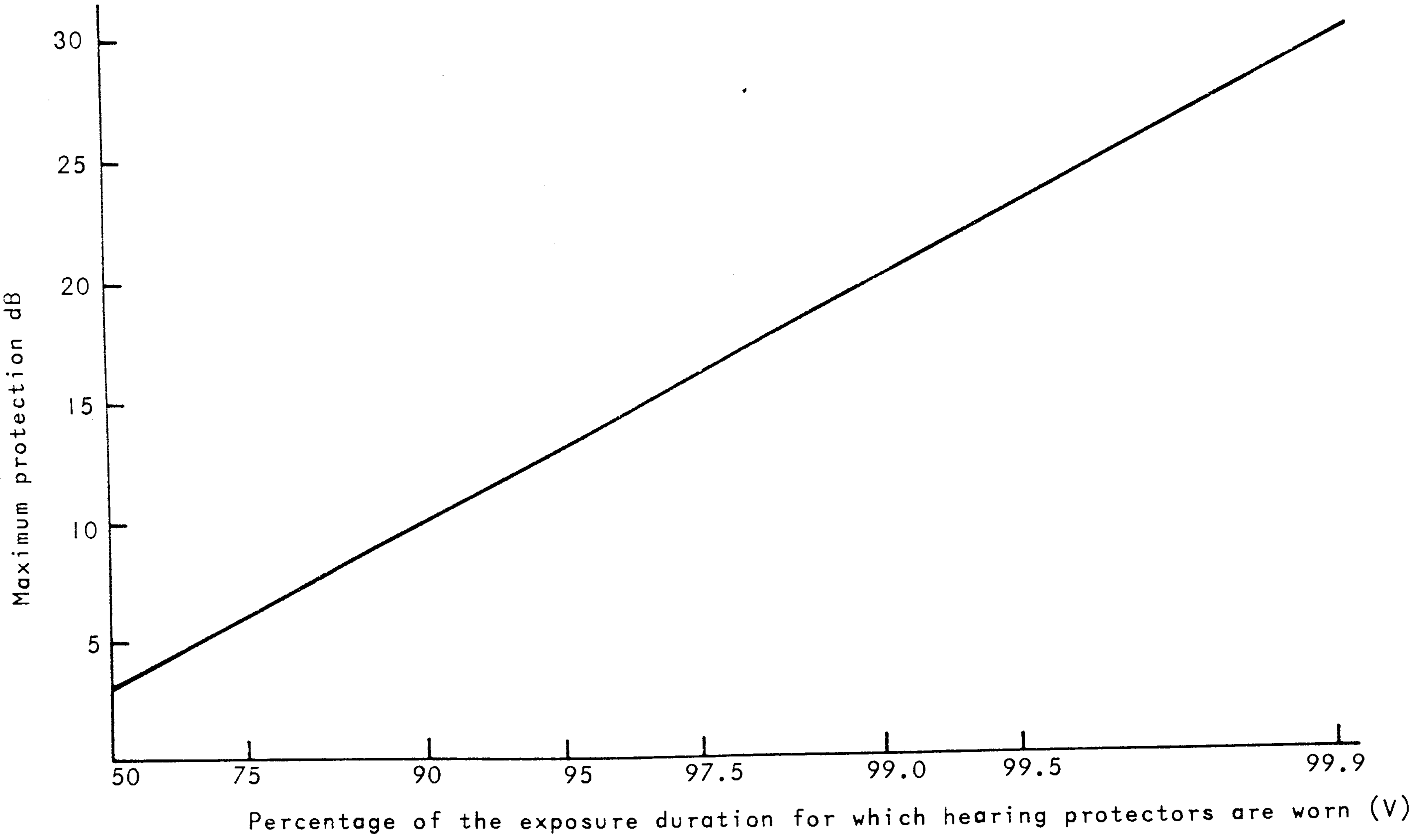


FIGURE 6

Protection Provided by Hearing Protectors as a Function of the Reduction in Sound Level they provide and the Percentage of the Exposure Duration for which They are Worn

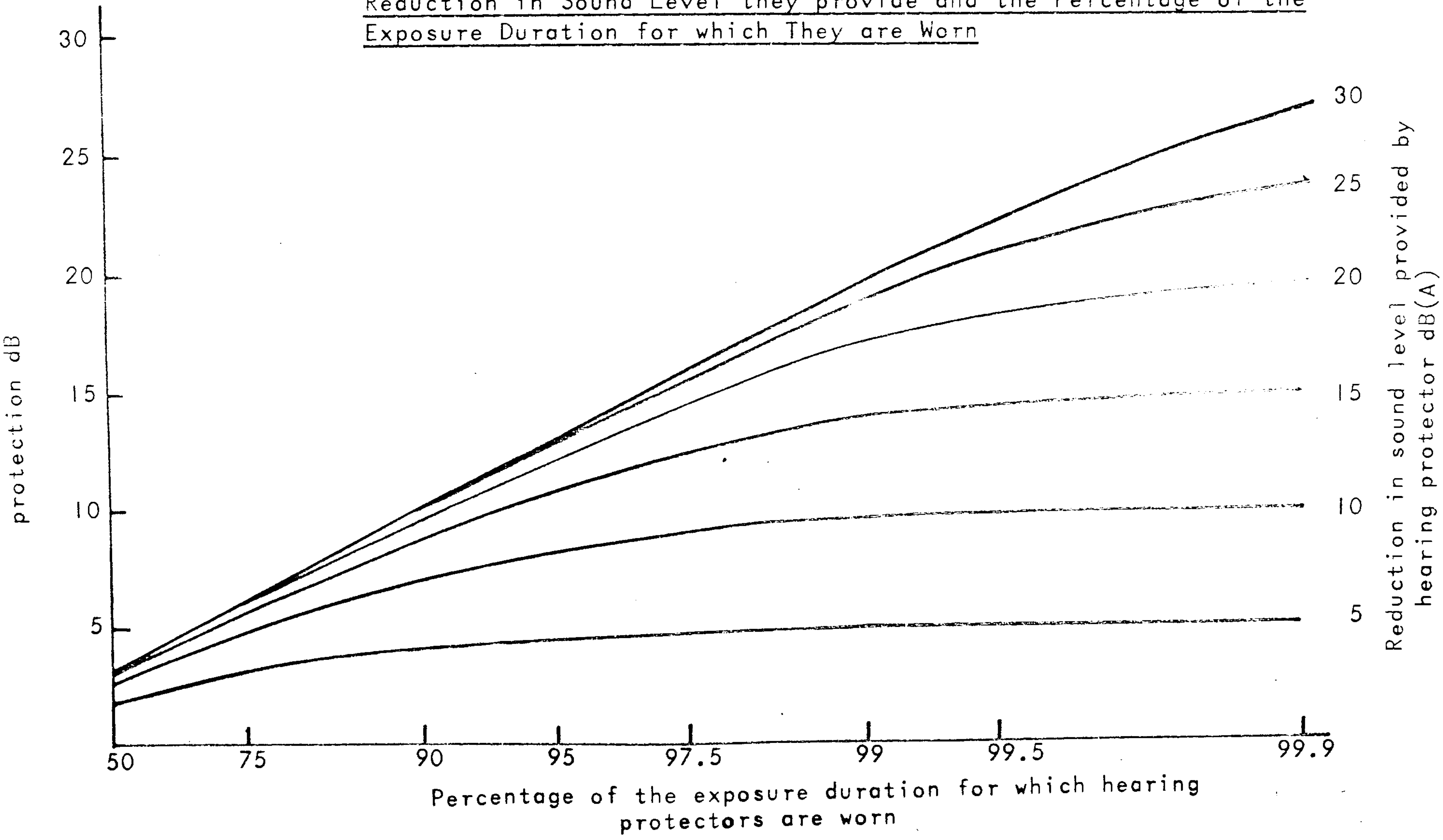


FIGURE 7

The Reduction in Noise Immission Level that can be Achieved by Providing Hearing Protectors Part-Way through a Person's 49 year Working Lifetime Exposure to Noise

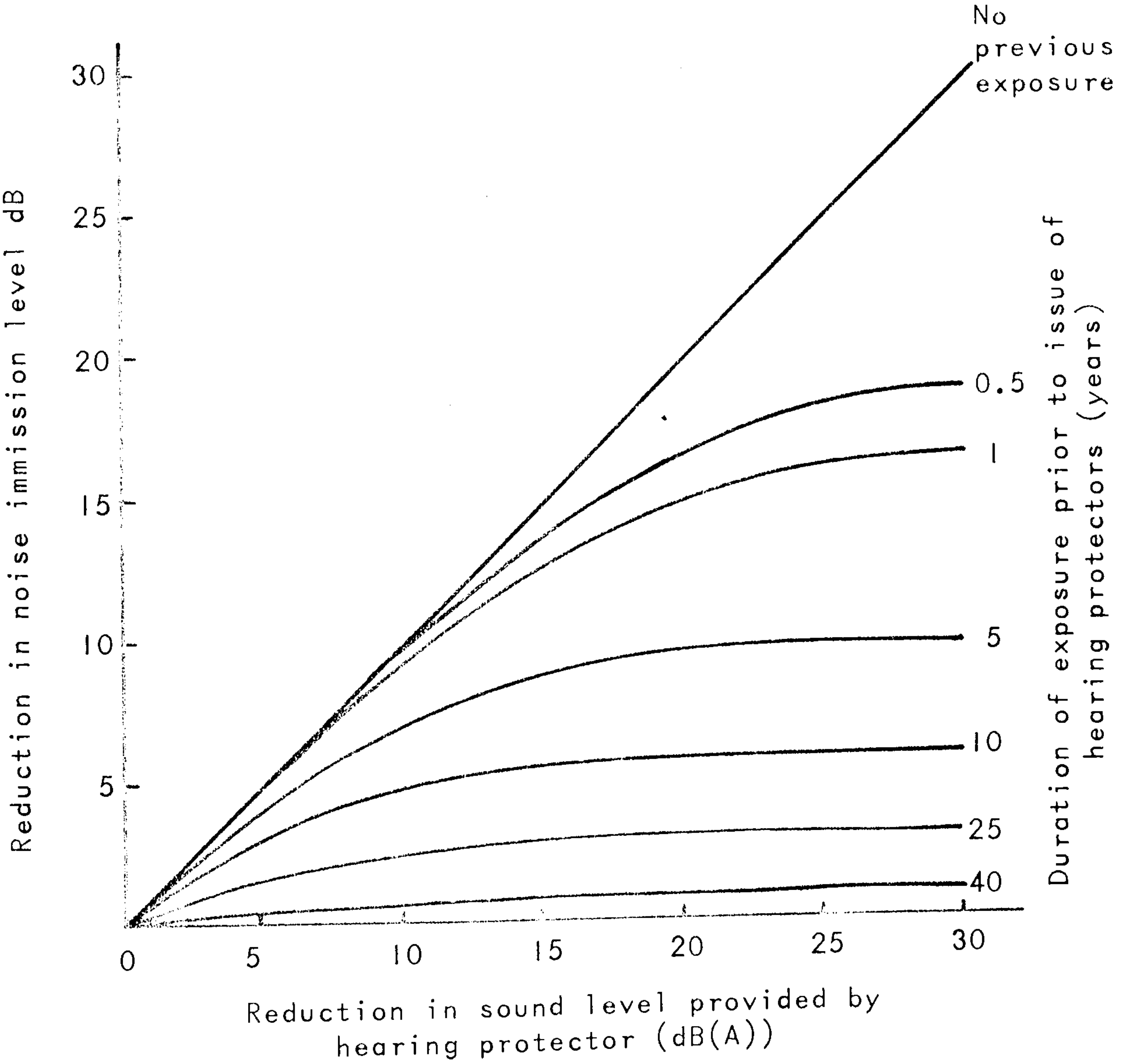


FIGURE 8

Residual Risk of exceeding $25dBHL_{\overline{0.512}}$, for Hearing Protector Users, following Exposure for a Working Lifetime of 49 Years to a Noise Level of 95dB(A)

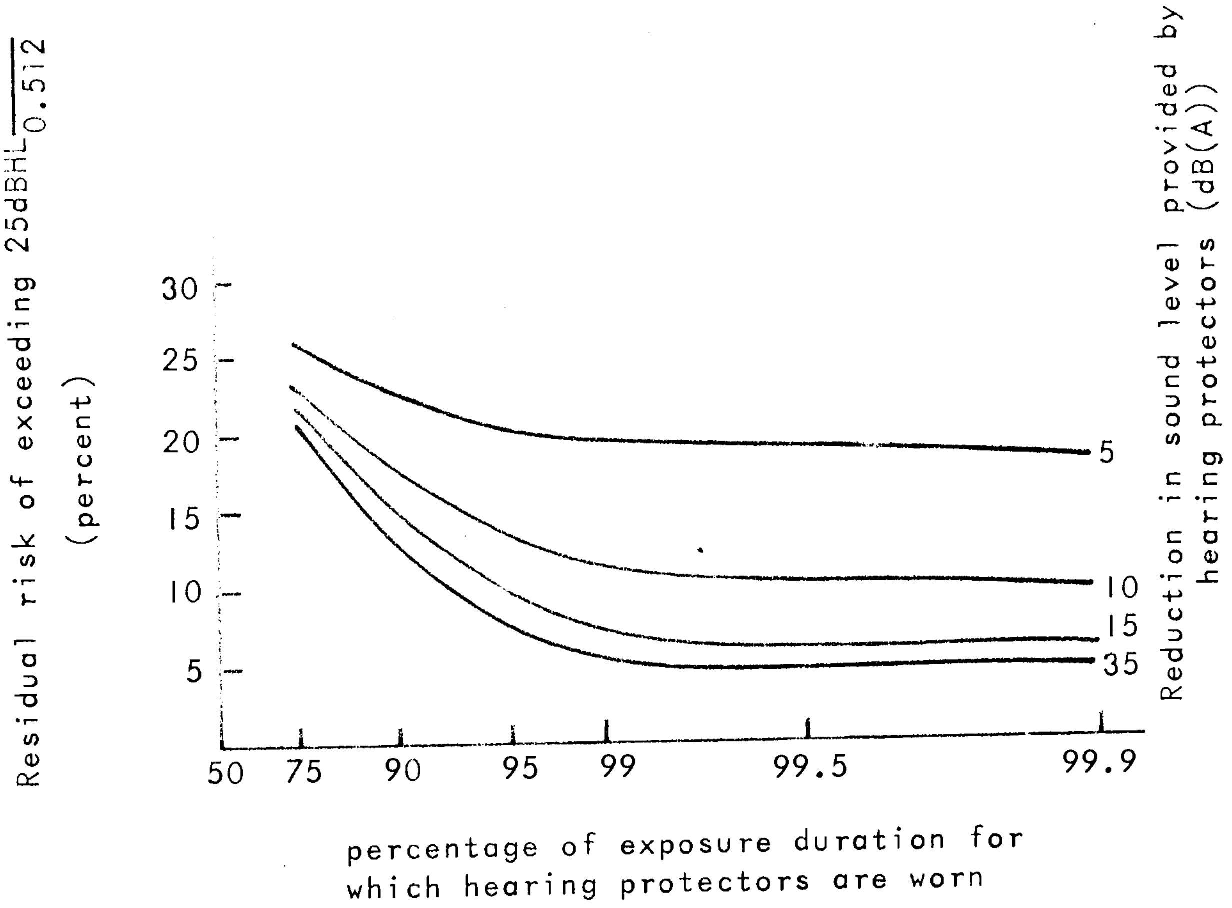


FIGURE 9

Residual Risk of Exceeding 25dBHL$\overline{0.512}$, for Hearing Protector Users, following Exposure for a Working Lifetime of 49 years to a Noise Level of 120dB(A)

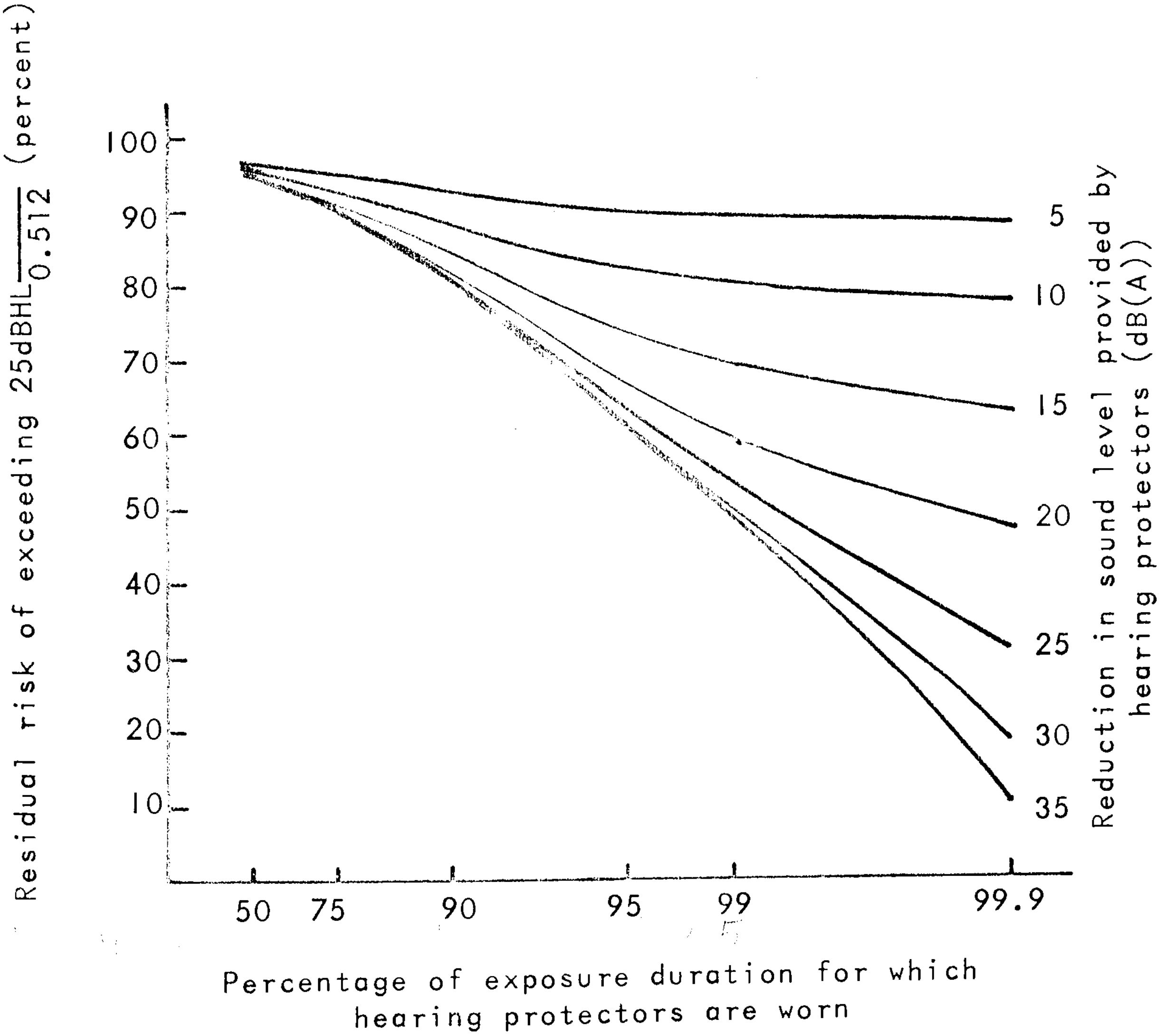


FIGURE 10

Residual Risk of Exceeding 25dBHL$_{0.512}$ for Population Exposed to 105dB(A) for a Working Lifetime of 49 Years: Variations with Percentage of Population Wearing Earplugs and Earmuffs

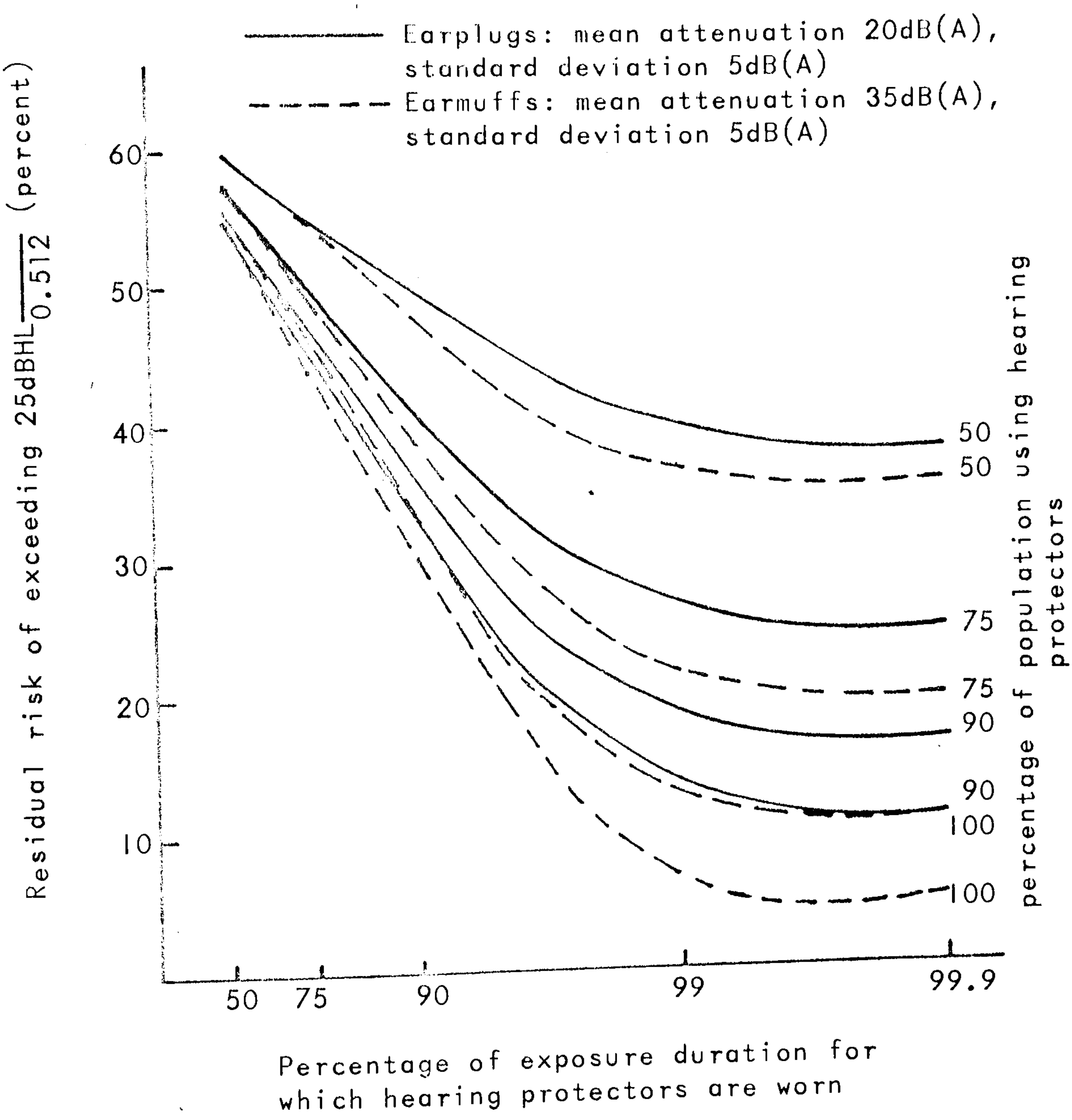


TABLE 3

Results of Continuous Observation and Noise Dose Measurement for one Swing-Frame Grinding operator during 4.5 hour morning shift

Activity whilst not wearing earmuffs	Duration of exposure whilst not wearing earmuffs (mins)	ECSL for the period during which earmuffs not worn (dB(A)
Cleaning and adjusting eye protectors at swing-frame grinder	2	99
Away from swing-frame grinder negotiating for more castings	6 6	94 - 100 94 - 100
Cleaning and adjusting eye protectors at swing-frame grinder	3	102
Walking to and from toilet	4	94

Estimated ECSL (8 hours) resulting from noise dose received when hearing protectors were not worn = 85dB(A) - 88.5dB(A)

Estimated ECSL (8 hours) if hearing protectors had not been worn = 104dB(A)

Estimated ECSL (8 hours) if earmuffs had been worn for total duration of exposure = 80dB(A)

Estimated ECSL (8 hours) if glass down earplugs had been worn for total duration of exposure = 91dB(A)

TABLE 4

Results of Continuous Observation and Noise Dose Measurement for one swing-frame grinding operator during 3.5 hour afternoon shift

Activity whilst not wearing earmuffs	Duration of exposure whilst not wearing earmuffs (mins)	ECSL for the period during which earmuffs not worn (dB(A))
Away from swing-frame grinder negotiating for more castings	4	94
Collecting water to damp floor before sweeping	2	90
Sweeping area around swing-frame grinders	15	99

Estimated ECSL (8 hours) resulting from noise dose received when hearing protectors not worn	=	88dB(A)
Estimated ECSL (8 hours) if protectors had not been worn	=	103dB(A)
Estimated ECSL (8 hours) if earmuffs had been worn for total duration of exposure	=	79 dB(A)
Estimated ECSL (8 hours) if glass down earplugs had been worn for the total duration of exposure	=	90dB(A)

TABLES AND FIGURES CHAPTER THREE

Tables 5 - 9

Figures 11 and 12

FIGURE 11

Simulated Recurrent Impact Noise Reproduced in Anechoic Room

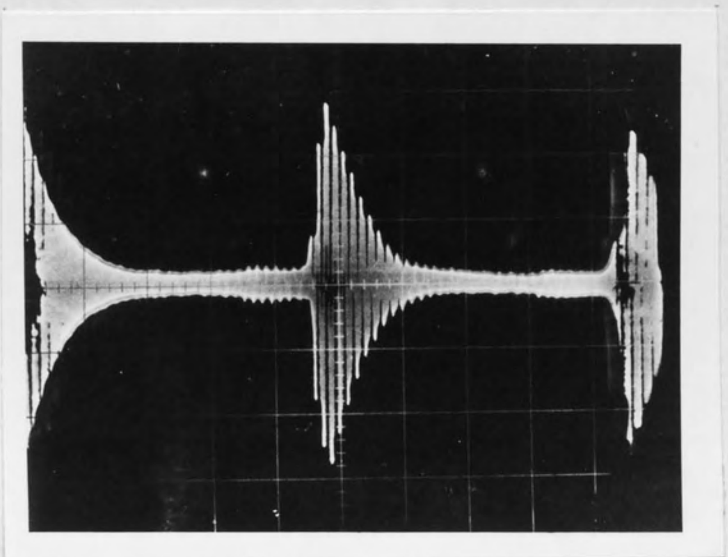


FIGURE 12

The Positions of the Six Loudspeakers Which Produced Impact Noise Stimuli and the Loudspeaker which Produced a Background of White Noise

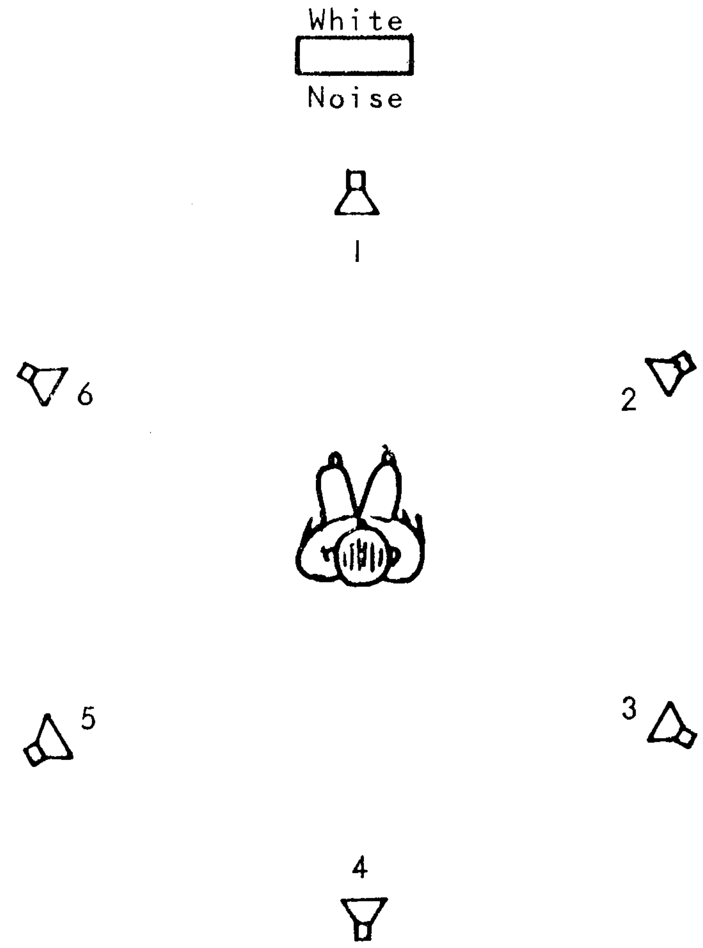


TABLE 5

The Number of Correct Responses Made by Each Subject in Each of the Listening Conditions for the Localisation Experiment with Impact Noise in Anechoic Chamber without Masking

Subject	Unoccluded	Earplugs	Earmuffs
1	10	9	4
2	12	12	12
3	12	12	6
4	10	9	6
5	5	9	5
6	10	9	5
7	9	9	4
8	8	10	6
9	10	10	7
10	11	11	8
Total - all subjects	97	100	63
Correct as a percentage of total presentations (120)	81	83	53

TABLE 6

Types of Errors made by the Group of Subject in Each of the Listening Conditions for the Localisation Experiment with Impact Noise in Anechoic Chamber Without Masking

Error Type with Respect to True Position	Number of errors in each listening condition			Percentage of total errors made in each listening condition		
	Unoccluded	Earplugs	Earmuffs	Unoccluded	Earplugs	Earmuffs
Forward	14	4	19	61	20	33
Rearward	9	16	38	39	80	67
One place forward	6	1	16	26	5	28
⩾ Two places forward	8	3	3	35	15	5
One place rearward	6	13	30	26	65	53
⩾ Two places rearward	3	3	8	13	15	14
One place	12	14	46	52	70	81
⩾ Two places	11	6	11	48	30	19

TABLE 7

The Number of Correct Responses Made by Each Subject in Each of the Listening Conditions for the Localisation Experiment with Masking

Subject	Unoccluded	Earplugs	Earmuffs
1	7	10	5
2	10	11	10
3	7	11	9
4	8	9	7
5	6	8	6
6	11	10	5
7	5	5	2
8	8	9	8
9	7	4	6
10	9	9	6
Total - all subjects	78	86	64
Correct as a percentage of total presentations (120)	65	71	53

TABLE 8

Types of Errors made by the Group of Subjects in Each of the Listening Conditions for the Localisation Experiment with Masking

Error Type with Respect to True Position	Number of errors in each listening condition			Percentage of total errors made in each listening condition		
	Unoccluded	Earplugs	Earmuffs	Unoccluded	Earplugs	Earmuffs
Forward	33	22	29	79	65	52
Rearward	9	12	27	21	35	48
One place forward	25	17	23	59	50	41
⩾ Two places forward	8	5	6	19	15	11
One place rearward	8	5	18	19	15	32
⩾ Two places rearward	1	7	9	2	21	16
One place	33	22	40	79	65	71
⩾ Two places	9	12	16	21	47	29

TABLE 9

A Summary of Results from Localisation Experiments in which Both Ears have been Occluded

	Experimental Conditions	Percentage of Total Responses Judged Correctly (ie error less than 30°)			Percentage loss in Localisation ability*	
		Unoccluded	Earplugs	Earmuffs	Earplugs	Earmuffs
Freedman and Fisher (1968)	White noise in anechoic conditions	75	-	44^{+}		41
Freedman (1969)	Speech in anechoic conditions	99	76	-		24
Atherley and Noble (1970)	1kHz pure tones in anechoic conditions	76	-	50		34
Atherley and Else (1971)	1kHz pure tones in reverberant conditions	55	-	40		27
Noble and Russell (1972)	1kHz pure tones in anechoic conditions	49	48	38	0	22

cont'd

Table 9 cont'd

Summary of Results from Localisation Experiments (cont'd)

	Experimental Conditions	Percentage of Total Responses Judged Correctly (ie error less than 30°)			Percentage loss in Localisation ability*	
		Unoccluded	Earplugs	Earmuffs	Earplugs	Earmuffs
Noble and Russell (1972)	White noise in anechoic conditions	95	83	68	13	28
Else Experiment 1	Impact noise in anechoic conditions	81	83	52	-2	36
Else Experiment 2	Impact noise in anechoic conditions in presence of white noise	65	72	53	-11	18

* Defined as the reduction in correct responses as a percentage of the number of correct responses in the unoccluded condition.

In the experiment of Freedman and Fisher the occluded conditions was used to negate the effect of pinnae; the earmuffs that were worn had tubes passed through the earmuff shells and the stimulus was increased in level by 8 decibels.

cont'd

Table 9 cont'd

In Freedman's experiment the occluded condition was used to negate the effect of pinnae. Molds were made for both ears of each subject from silicone rubber; the molds filled the convolutions and back of the pinnae leaving only a small opening opposite the auditory canal.

The experiments of Freedman, and Freedman and Fisher, used sixteen loudspeakers at a spacing of $22\frac{1}{2}$ degrees; their data have been transformed approximately for comparison purposes and a correct response has been defined as a response to the stimulus speaker position or to one of the speakers on either side.

TABLES AND FIGURES CHAPTER FOUR

Tables 10 - 23

Figures 13 - 29

TABLE 10

Summary of Occupations and Noise Exposures of 'Fettler' Subject Group

Occupation	No. of Subjects participating in experiments	Highest Measured Sound Level dB(A)	Equivalent Continuous Sound Level dB(A)
Arc-Air Operators Work in booths: arc struck between hand-held electrode and casting; molten metal moved from arc by compressed air jet incorporated in electrode holder	3	117	112 - 115
Welders Work at ventilated benches; manual arc welding used to fill imperfections in castings	3	100*	94 - 96
Burners Work at ventilated fettling benches: oxy-acetylene hand-held or jig-mounted torch used to cut off risers and divide multiple castings	4	104	101 - 104
Dressers Work at benches. Pneumatic chipping hammers used to remove flash from castings	7	125	122 - 124

cont'd

Table 10
cont'd

Summary of Occupations (cont'd)

Occupation	No. of Subjects participating in experiments	Highest Measured Sound Level dB(A)	Equivalent Continuous Sound Level dB(A)
Portable Grinder Operators Work at ventilated fettling benches: high speed portable grinding wheels used to remove flash and shape castings	3	98*	94 - 96
Service Labourers Work anywhere in the fettling shop, assisting with movement of castings and other materials	1	125*	94 - 100

* The highest noise levels measured in the vicinity of these fettlers was produced by other processes.

** The ECSLs were estimated from noise levels measured at the operators' ears and duration estimates provided by supervisors. They are approximate values only.

TABLE II

Distribution of Ages in the Two Subject Groups

	Age in Years				
	16-25	26-35	36-45	46-55	56-65
Fettlers	F1* (17)	F6 (30)	F4* (43)	F2* (49)	F3 (62)
	F9* (17)	F11+(28)	F7 (40)	F5+ (53)	F17 (64)
	F12 (25)	F13+(31)	F8 (39)	F10+(49)	F19 (59)
	F21 (20)	F18*(28)	F15 (43)	F14*(46)	F20 (62)
Office Employees	05 (19)	01 (30)	08 (40)	02 (55)	03 (58)
	010 (21)	04 (28)	09 (39)	011 (46)	06 (64)
	013 (23)	07 (29)	014 (36)		
		012 (31)	015 (40)		
		016 (28)			
		017 (30)			
		018 (26)			

* glass down earplug user

\+ earmuff user

FIGURE 13

Comparison of the Distribution of Average Hearing Levels (both ears) for the Two Subject Groups

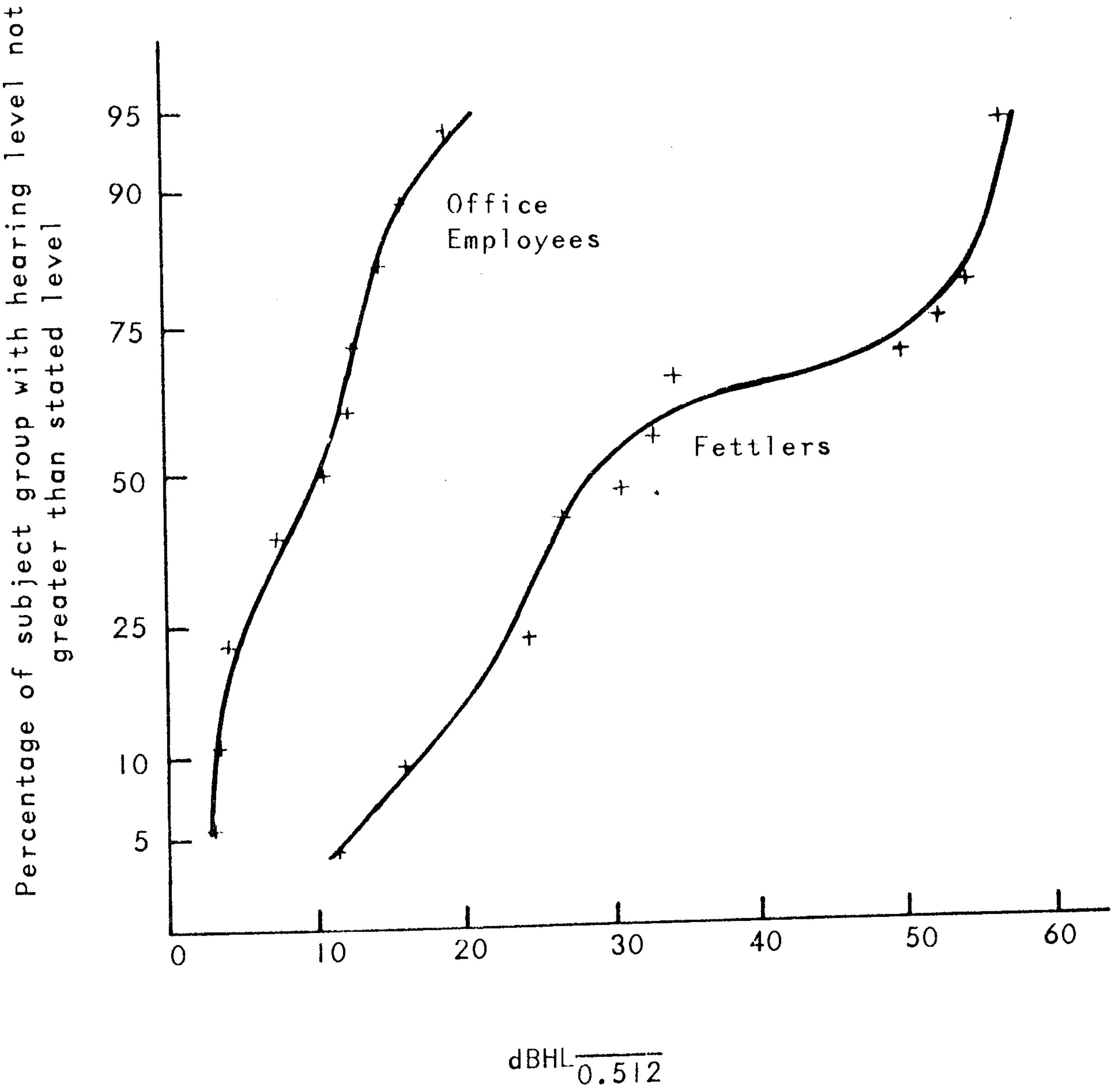
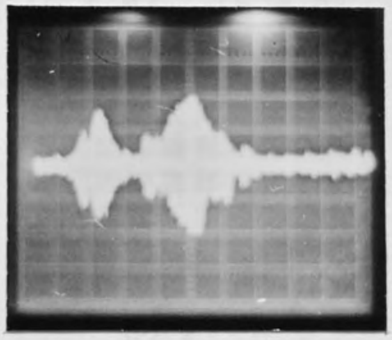
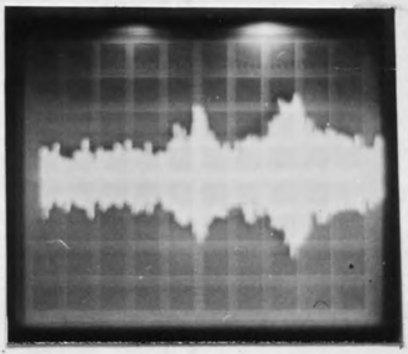


FIGURE 14

Pressure-time Characteristics of Shouted Warning "Watch Out": (a) in quiet and (b) in 75dB(A) background of "pink" noise



(a)



(b)

0.1 seconds per division

0.12 pascal per division

FIGURE 15

Schematic Diagram of Equipment Used in the Foundry Localisation Experiments to: Generate Warning Shouts and Pink Background Noise; and Measure Subjects' Response Times

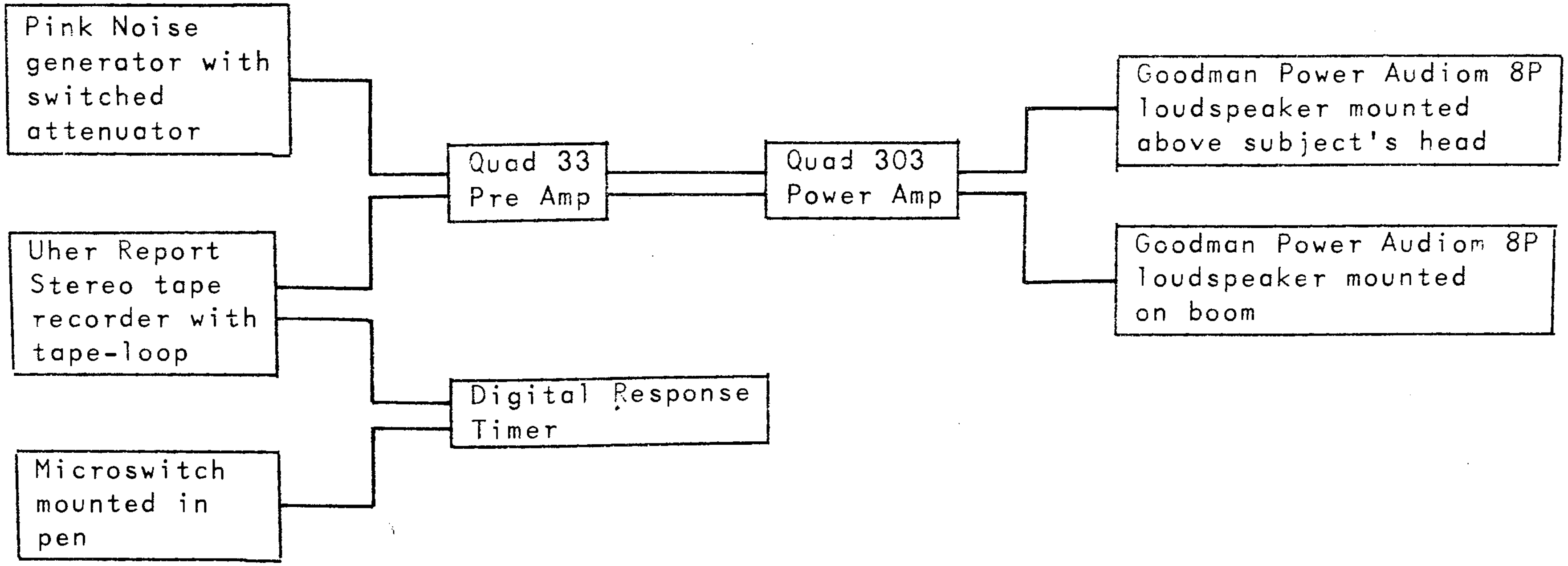


FIGURE 16

Loudspeaker Positions From Which the Warning Shout was Presented

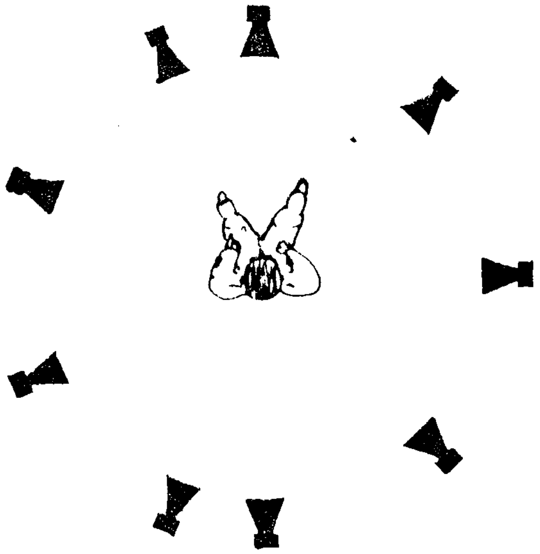
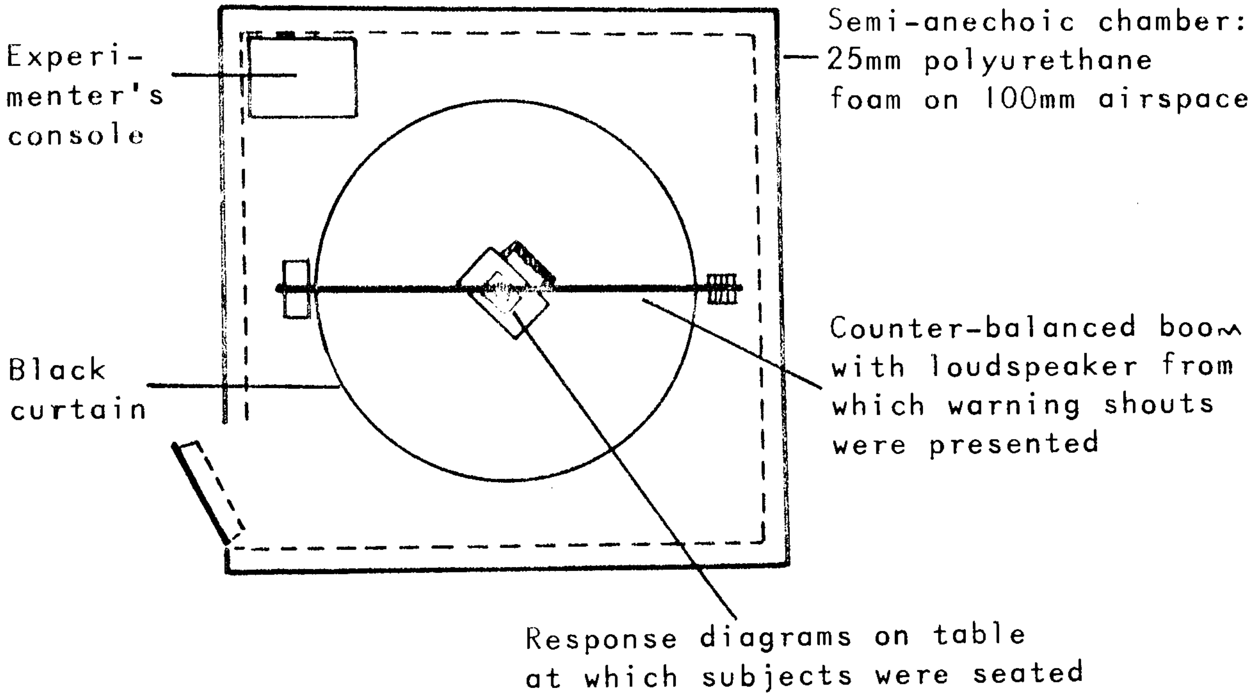


FIGURE 17

Apparatus Used to Present Recorded Warning Shouts at Head Height from Many Directions Around the Seated Subject Against Background Noise in the Semi-anechoic Chamber



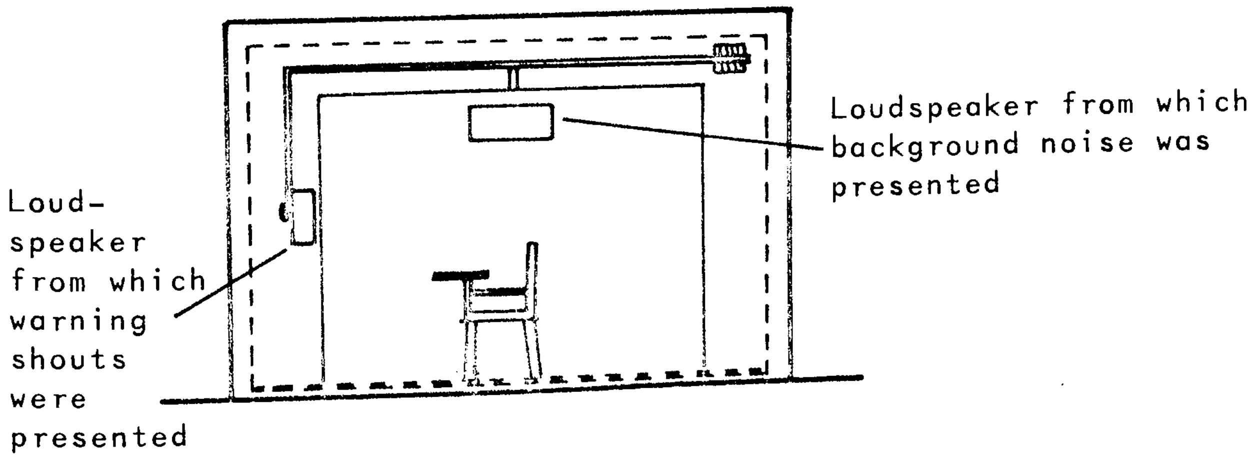


FIGURE 18

Response Diagram - The Subject Was Asked to Mark the Circle at the Position from which He Thought the Sound Had Originated

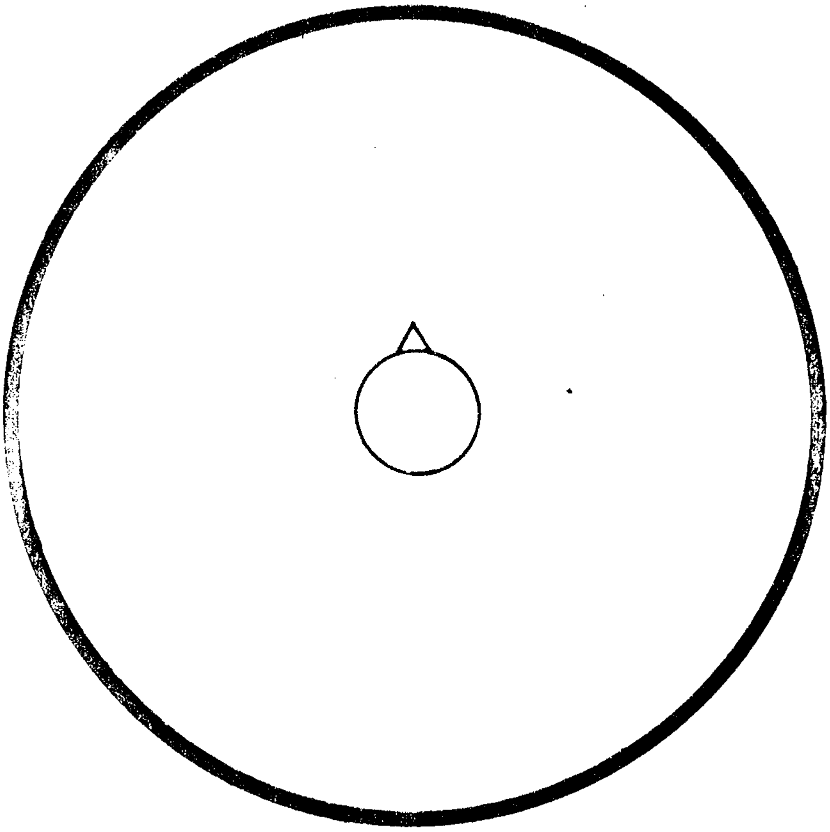
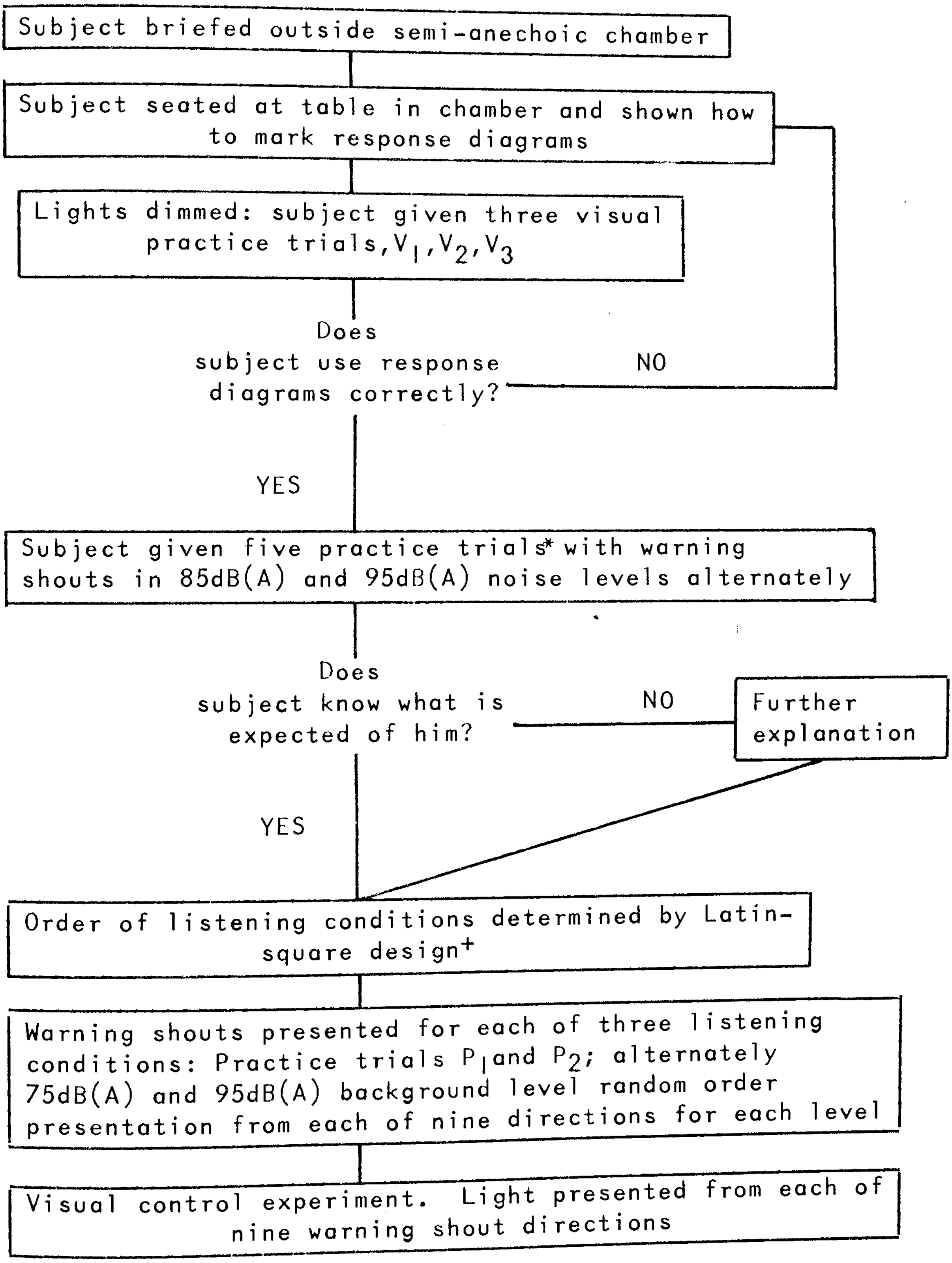


FIGURE 19

Flowchart Illustrating Procedure Followed with Each Subject During Localisation Studies at the Foundry

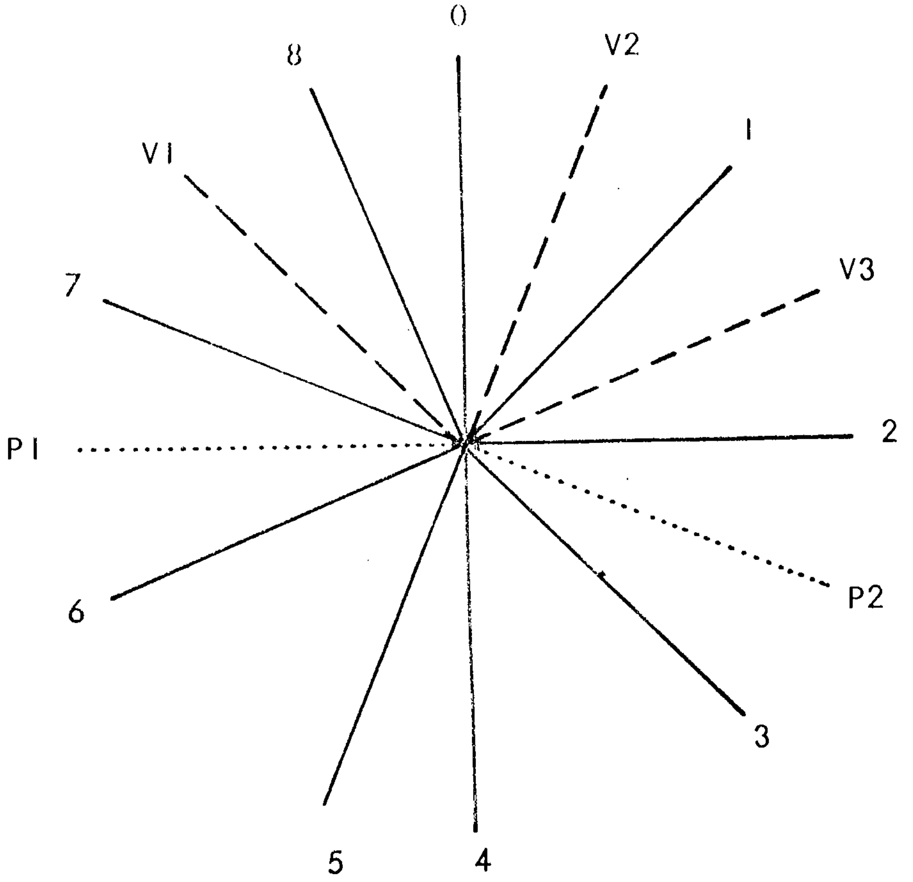


* random selection from nine stimulus directions 0 - 8

\+ Table 12

FIGURE 20

Directions from which Visual and Auditory Test Stimuli and Practice Stimuli were Presented



—————— 0 1 2 3 4 5 6 7 8 Positions from which warning shouts were presented*

– – – – – V1 V2 V3 Positions used for visual practice

.... P1 P2 Position used for auditory practice

* Positions 0 1 2 3 4 5 6 7 8 were also used during the visual control experiment.

TABLE 12

The Order of Presentation of listening Conditions (Unoccluded ears; Earplugs in Ears; Earmuffs over Ears) for the Subjects with the Two Groups - a Latin Squares Design

Subject	Order of Hearing Conditions		
	First	Second	Third
F1	P	N	M
F2	N	M	P
F3	M	P	N
F4	P	M	N
F5	M	N	P
F6	N	P	M
F7	N	P	M
F8	P	M	N
F9	M	N	P
F10	N	M	P
F11	M	P	N
F12	P	N	M
F13	P	M	N
F14	N	P	M
F15	M	N	P
F16	P	N	M
F17	M	P	N
F18	N	M	P
F19	M	N	P
F20	N	P	M
F21	P	M	N

Subject	Order of Hearing Conditions		
	First	Second	Third
01	P	M	N
02	N	P	M
03	M	N	P
04	M	N	P
05	N	P	M
06	P	M	N
07	M	N	P
08	P	M	N
09	N	P	M
010	M	P	N
011	P	N	M
012	N	M	P
013	P	N	M
014	N	M	P
015	M	P	N
016	P	M	N
017	M	N	P
018	N	P	M

N = unoccluded ears
P = earplugs in ears
M = earmuffs over ears

F1 to F21 refer to Fettlers
01 to 018 refer to Office Employees

Note The order resulted from randomly selecting 7 3x3 Latin Squares from the twelve possible 3x3 Latin Squares - independently for each subject.

TABLE 13

Warning Shouts Missed by the Two Groups in Each Listening Condition for High and Low Background Noise Levels

	Background Noise Level	Number of warning shouts missed Unoccluded	 Earplugs	 Earmuffs
Office employees	75dB(A)	0	0	0
	95dB(A)	3	3	4
Fettlers	75dB(A)	0	0	1
	95dB(A)	5	9	31

Note: There were 18 subjects in the office employee group and 21 in the group of fettlers. Each cell represents the number missed out of a total of 162 presentations for the office employee group and 189 for the fettler group.

FIGURE 21

Correlation Between Hearing Levels and Numbers of Warning Shouts Missed Whilst Earmuffs Were Worn

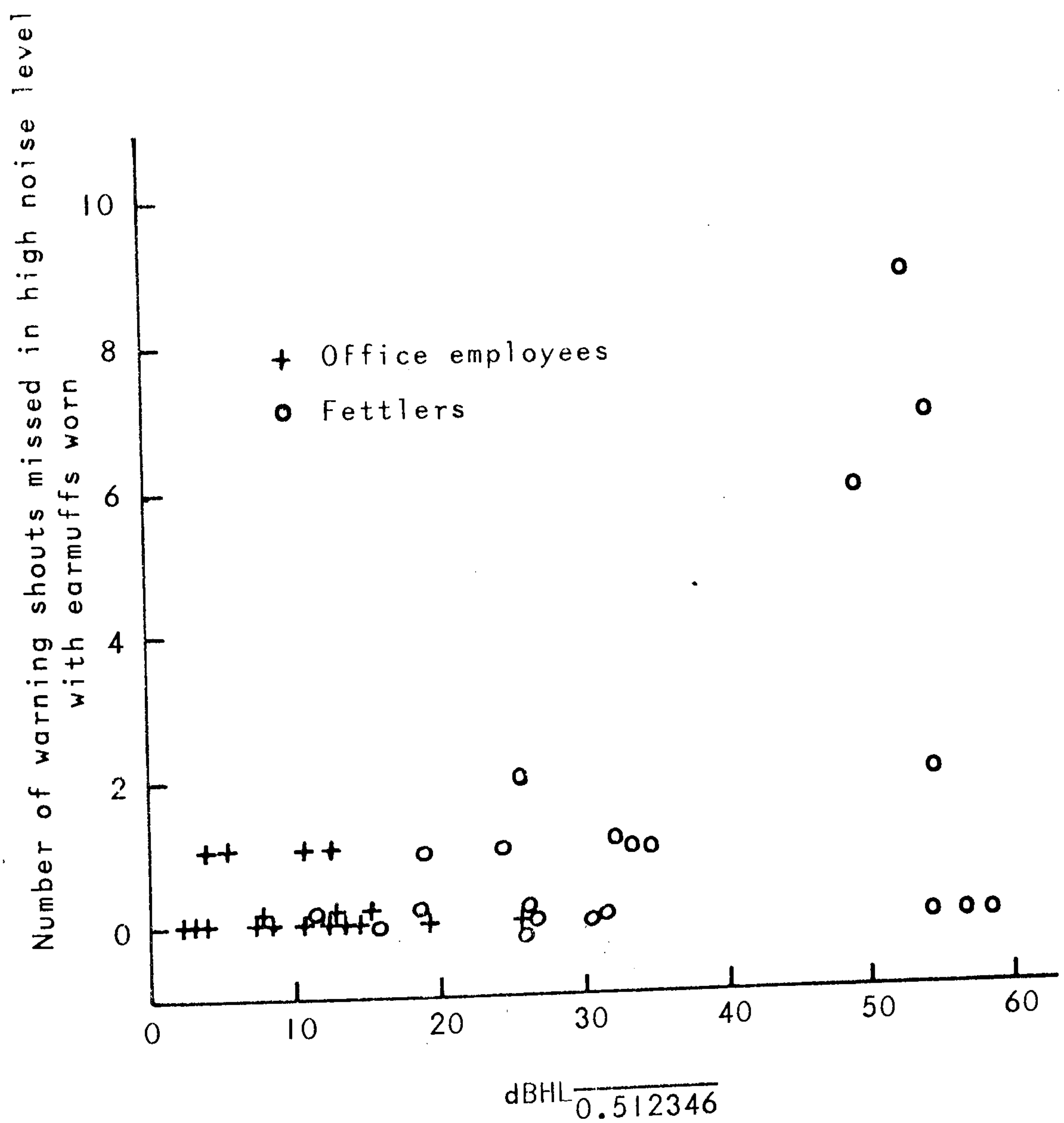


FIGURE 22

Total Numbers of Warning Shouts Missed at Each Stimulus Position for Each Listening Condition - subject groups and background noise levels combined

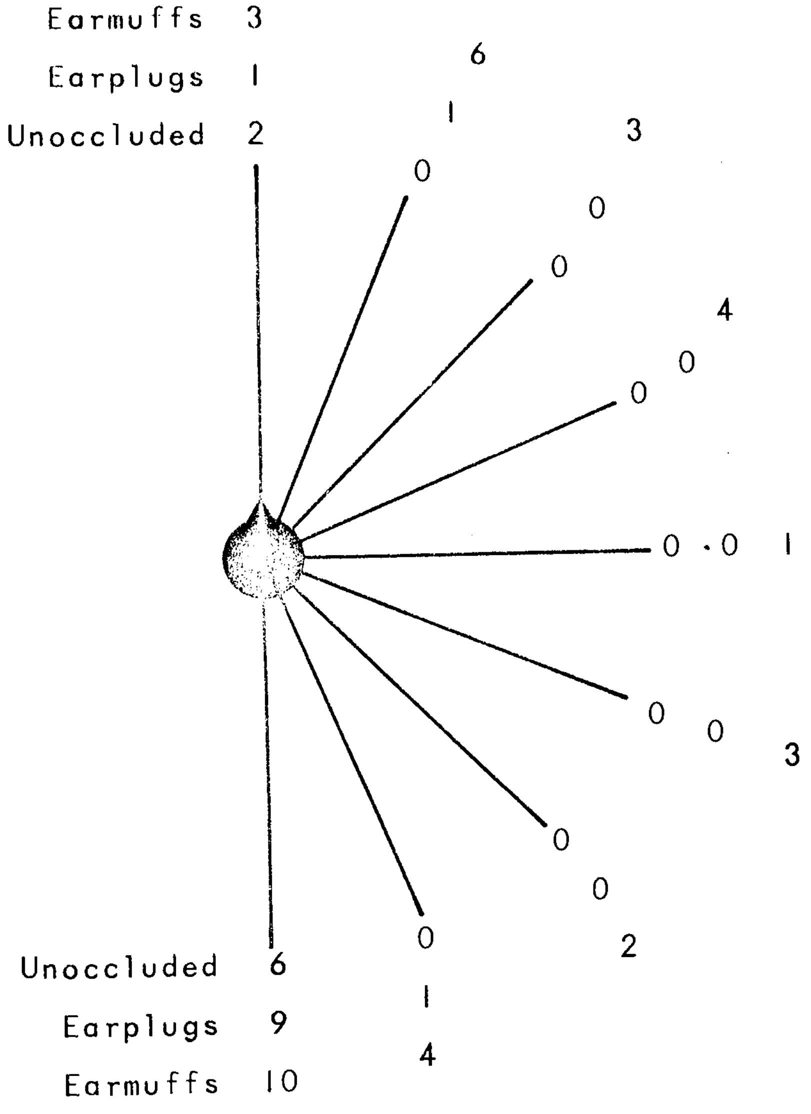


TABLE 14

Average Response Times for Warning Shouts from Each of the Nine Directions; Office Employee Subject Group (Off) and Fettler Subject Group (Fet)

Stimulus Position	Response Times (seconds)											
	Background Noise Level 75dB(A)						Background Noise Level 95dB(A)					
	Unoccluded		Earplugs		Earmuffs		Unoccluded		Earplugs		Earmuffs	
	Off	Fet	Off	Fet	Off	Fet	Off	Fet	Off	Fet	Off	Fet
0	3.5	3.7	3.7	3.6	3.3	3.7	4.2	3.5	3.9	3.5	3.9	3.5
1	2.8	3.2	2.8	2.9	3.1	3.4	2.9	2.7	3.6	3.3	3.4	3.2
2	2.8	3.0	2.7	2.9	3.1	3.1	3.3	3.3	3.0	3.1	3.0	3.6
3	2.9	2.8	2.9	2.7	3.1	2.8	2.8	3.1	3.2	3.0	3.5	4.0
4	3.1	3.6	3.6	3.7	3.6	3.8	3.6	3.4	5.5	4.8	4.2	4.2
5	3.2	3.3	3.1	3.2	3.1	3.4	3.0	3.6	3.6	4.0	3.7	3.6
6	2.8	2.8	2.9	2.9	3.1	2.9	2.8	3.1	2.9	3.6	3.7	3.6
7	2.9	3.1	2.9	3.1	2.6	3.1	3.1	3.6	3.5	3.6	4.1	4.1
8	3.0	3.7	3.0	3.6	3.2	3.4	3.8	3.9	3.9	4.0	3.7	4.4
Mean	3.0	3.2	3.1	3.2	3.1	3.3	3.3	3.4	3.7	3.7	3.7	3.8

FIGURE 23

Variation in Response Time with Stimulus Direction for Warning Shouts Detected in 75dB(A) 'pink' noise - Subject Groups Combined

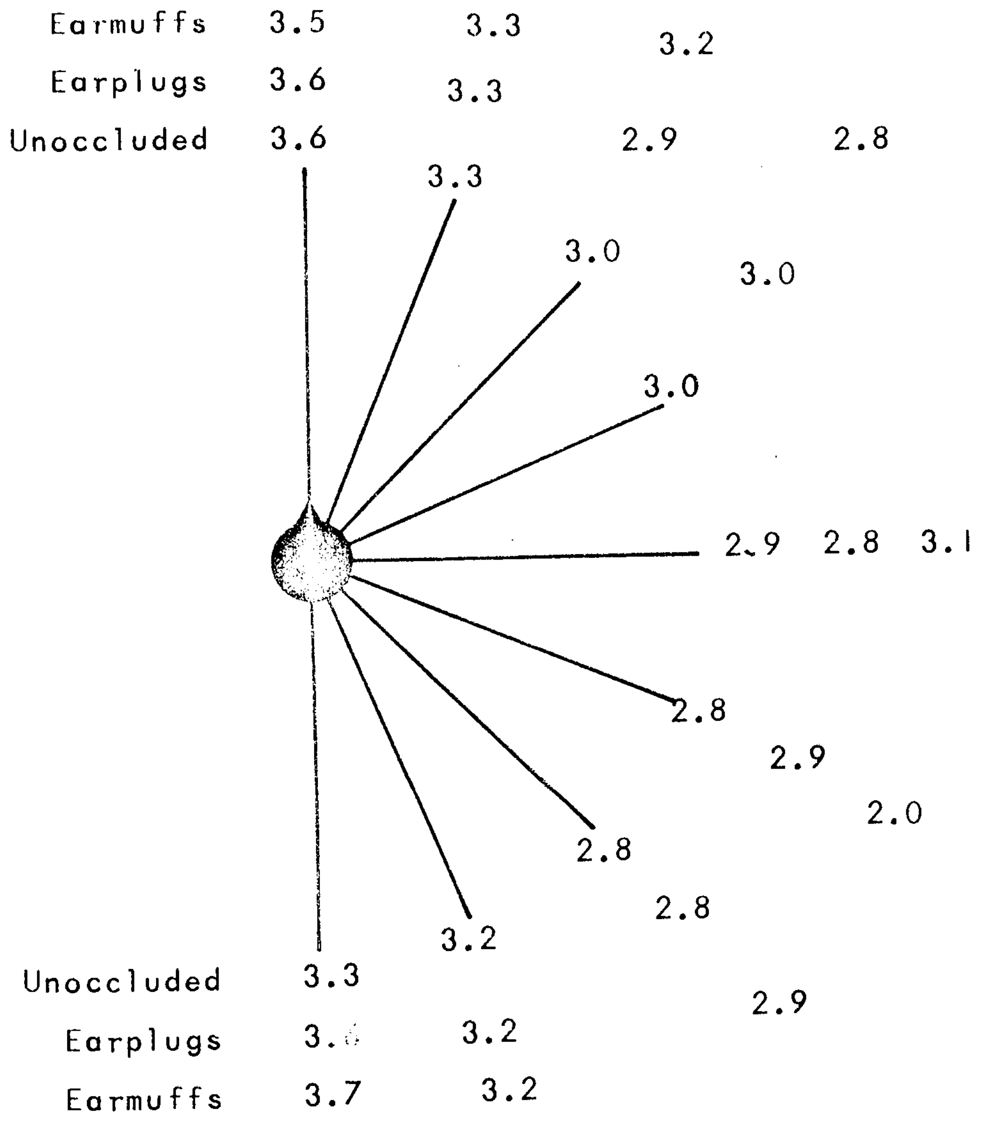


FIGURE 24

Variation in Response Time with Stimulus Direction for Warning Shouts Detected in 95dB(A) 'pink' noise - Subject Groups Combined

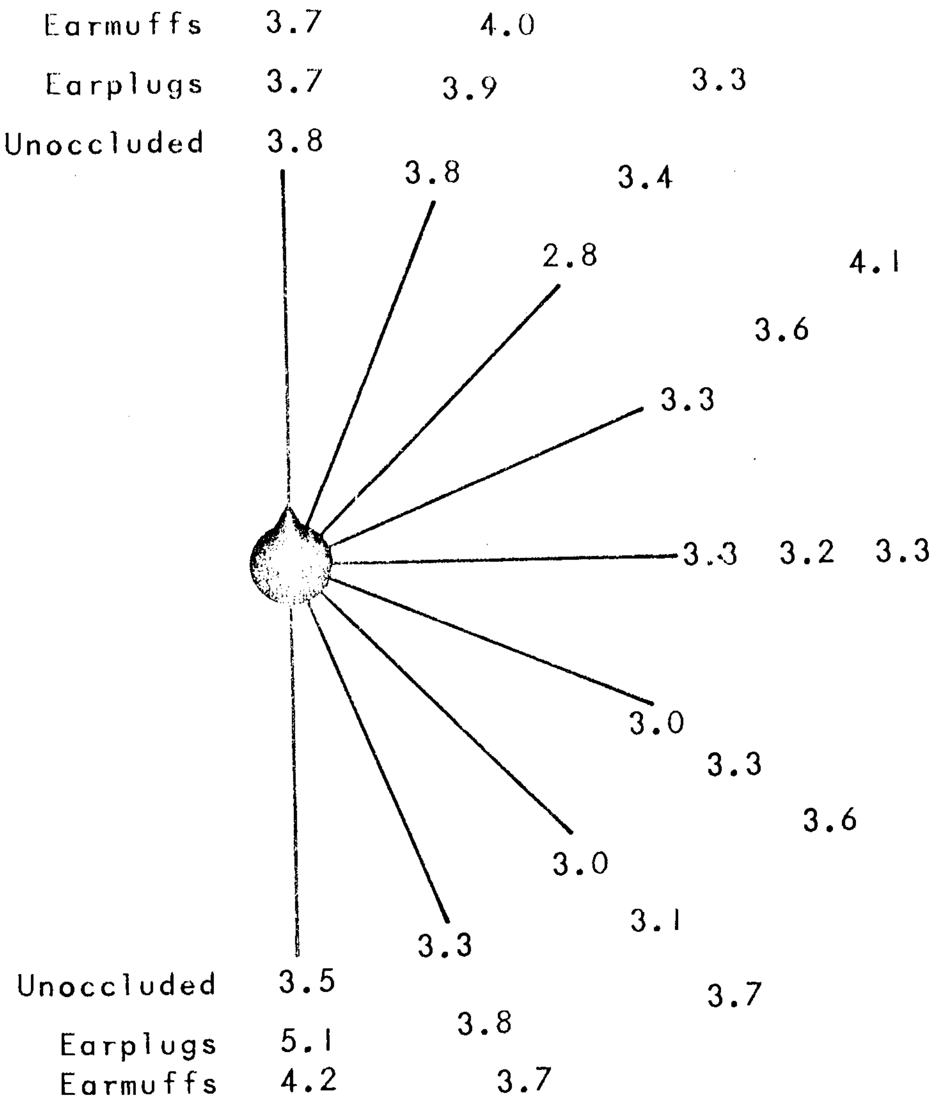


TABLE 15

Total of times taken to Respond to Nine Warning Shouts; One from Each of the Nine Directions. Data for Subjects who Responded to all Shouts: Six Fettlers and Seven Office Employees

Subject	Response Time in Seconds (sum of nine responses) Background Noise Level 75dB(A)			Background Noise Level 95dB(A)		
	Unoccluded	Earplugs	Earmuffs	Unoccluded	Earplugs	Earmuffs
F2	27.7	42.2	29.3	36.6	46.0	41.0
F3	26.6	26.4	29.3	30.3	33.5	31.5
F5	25.3	22.2	24.8	21.0	21.8	31.0
F8	24.9	25.2	26.3	24.0	35.2	29.8
F9	27.4	27.2	31.2	30.9	25.8	28.1
F11	23.4	27.4	33.9	23.9	30.5	42.9
01	23.9	24.2	21.9	25.1	27.9	21.9
04	35.2	37.3	39.6	37.1	35.6	36.6
05	35.5	48.9	35.7	41.2	53.9	44.0
011	17.3	16.2	18.9	17.8	17.9	19.3
012	33.0	22.2	30.1	31.7	29.1	50.3
014	17.5	17.7	18.7	21.1	19.9	21.2
017	27.9	21.5	39.7	34.9	35.9	42.9

TABLE 16

Total Angular Error (degrees) made Whilst Responding to Nine Warning Shouts, one from Each of the Nine Directions. Data for Subjects who Responded to All Shouts: Eight Fettlers and Eleven Office Employees

Subject	Background Noise Level 75dB(A) Unoccluded	Earplugs	Earmuffs	Background Noise Level 95dB(A) Unoccluded	Earplugs	Earmuffs
F1	165	350	168	420	696	412
F2	366	391	401	361	478	564
F3	185	444	593	356	530	603
F5	324	419	401	510	575	550
F8	350	326	383	472	557	629
F9	447	114	518	612	445	524
F11	286	486	233	443	475	420
F18	341	371	390	580	610	601
01	386	366	440	446	555	691
02	135	480	535	422	593	514
03	236	426	211	738	588	869
04	439	480	495	501	250	591
05	352	376	368	555	415	694
06	359	423	411	386	574	882
07	450	88	421	261	398	726
011	365	465	776	515	602	769
012	172	169	348	555	473	696
014	206	346	416	667	271	858
017	349	280	231	596	476	808
Means:						
Fettlers	308	363	385	469	546	538
Office Employees	314	355	423	513	472	736
Fettlers and Office Employees	311	358	407	495	503	653

FIGURE 25

Correlation Between Hearing Levels and Total Angular Error When Earmuffs were worn in the Higher Background Noise Level 95dB(A)

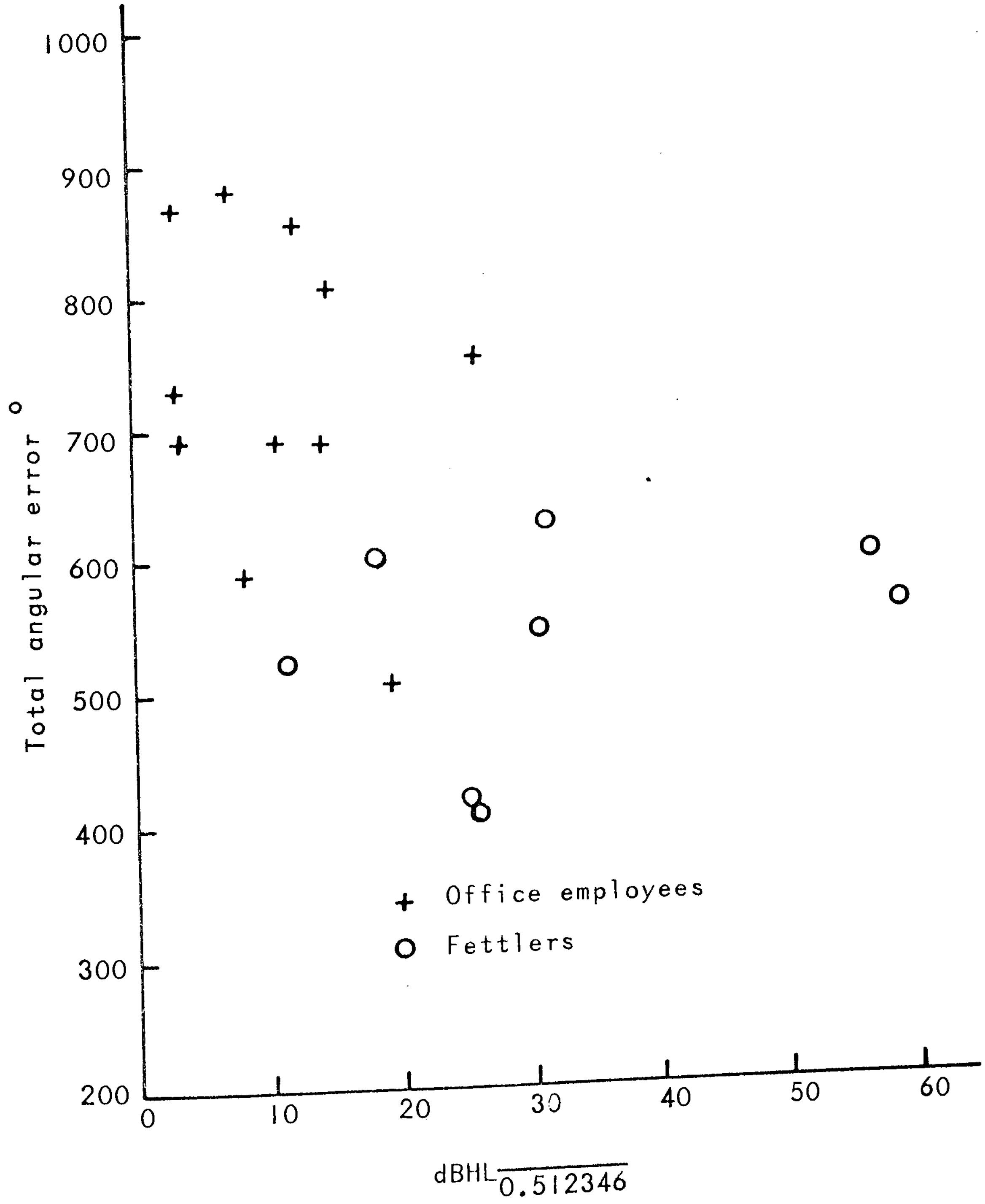


FIGURE 26

Correlation Between Hearing Levels and Total Angular Error When Earmuffs were worn in the Lower Background Noise Level 75dB(A)

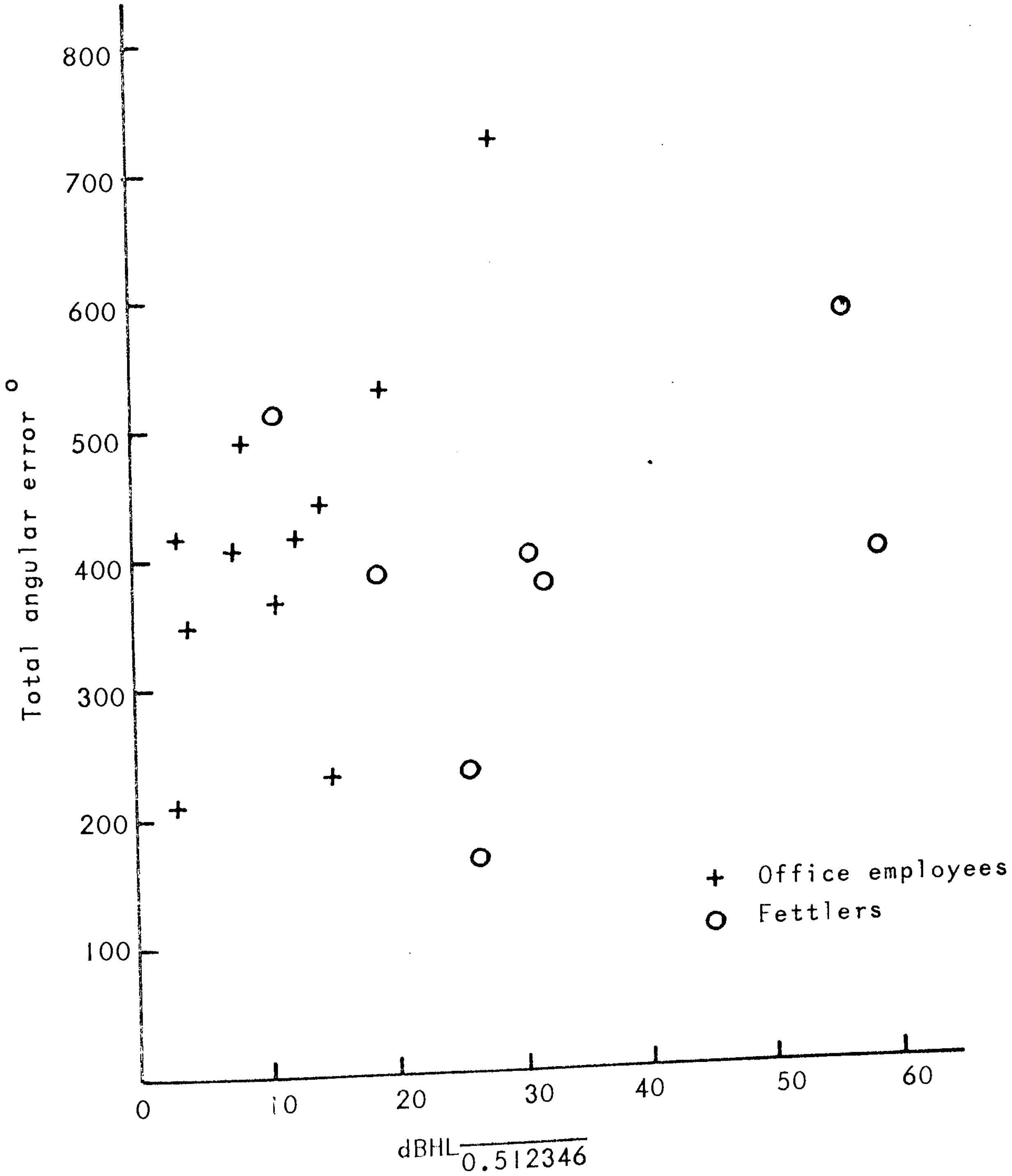


TABLE 17

Mean Response Error for Warning Shouts from Each of the Nine Directions - Mean from Eighteen Office Employees

Stimulus Position	Mean Response Error (degrees)					
	Background Noise Level 75dB(A)			Background Noise Level 95dB(A)		
	Unoccluded	Earplugs	Earmuffs	Unoccluded	Earplugs	Earmuffs
0	64.3	72.8	80.8	114.1	115.9	121.6
1	22.4	28.9	36.5	39.3	49.4	87.6
2	13.1	14.0	16.9	30.5	19.1	42.2
3	44.5	38.5	47.0	45.3	37.2	46.7
4	59.2	63.8	66.5	48.6	53.7	60.9
5	36.2	38.9	51.3	43.4	58.7	74.3
6	15.4	16.7	21.6	51.1	30.6	76.5
7	17.6	25.9	28.8	39.5	33.2	76.5
8	44.7	54.7	48.1	112.6	91.6	123.3

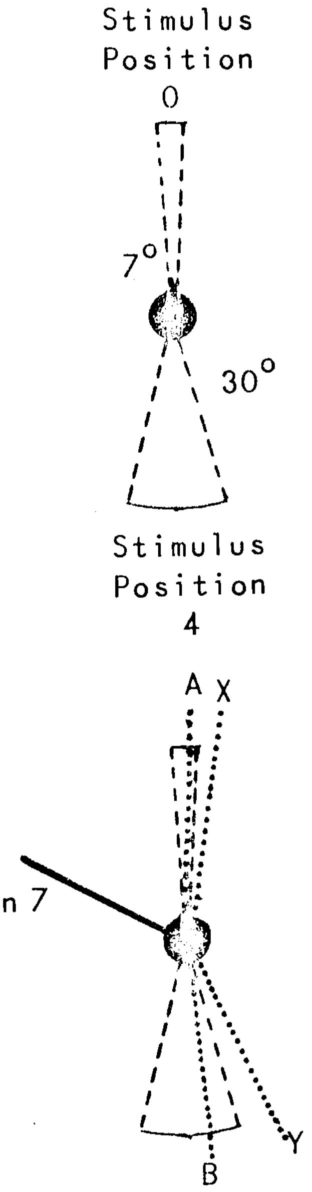
TABLE 18

Mean Response Error for Warning Shouts from Each of the Nine Directions - Mean from Twenty-One Fettlers

Stimulus Position	Mean Response Error (degrees) Background Noise Level 75dB(A) Unoccluded	Earplugs	Earmuffs	Background Noise Level 95dB(A) Unoccluded	Earplugs	Earmuffs
0	56.2	66.2	80.1	119.9	147.8	112.5
1	34.6	36.1	35.0	61.1	74.9	74.2
2	9.6	10.4	19.3	30.7	46.2	62.2
3	38.2	37.0	37.4	38.9	43.2	44.6
4	68.0	50.8	73.0	52.9	69.7	56.3
5	42.4	38.3	31.1	43.3	37.9	45.5
6	17.3	18.7	27.8	26.0	37.7	39.4
7	20.1	29.0	36.3	44.9	36.4	56.5
8	62.0	90.8	74.9	81.0	107.4	109.1

FIGURE 27

Contralateral Response Classification Scheme



Region within which 95% of visual control responses to stimulus at position 0 were placed

Region within which 95% of visual control responses to stimulus at position 4 were placed

Example of contralateral response classification

Stimulus warning shout from position 7

Responses placed at X,Y classified as contralateral responses

Responses at A,B not classified as contralateral responses

TABLE 19

Contralateral Responses to Nine Warning Shouts, One from Each of the Nine Directions for the Twenty-One Fettlers

Subject	Background Noise Level 75dB(A) Unoccluded	Background Noise Level 75dB(A) Earplugs	Background Noise Level 75dB(A) Earmuffs	Background Noise Level 95dB(A) Unoccluded	Background Noise Level 95dB(A) Earplugs	Background Noise Level 95dB(A) Earmuffs
F1+	0	0	0	0	1	0
F2+	0	0	0	0	0	1
F3+	0	0	3	1	0	1
F4	0	0	0	0	1	0
F5+	0	0	0	0	2	1
F6	0	0	0	0	0	1
F7+	0	0	0	0	0	4
F8+	0	0	0	0	0	2
F9+	0	0	0	2	1	2
F10	0	0	0	1	0	2
F11+	0	0	0	0	0	0
F12+	0	0	0	1	0	0
F13	0	0	0	1	0	2
F14+	0	1	0	1	1	0
F15	0	0	0	0	2	1
F16	0	0	0	1	3	0
F17	0	0	2	1	2	4
F18+	0	0	0	1	1	3
F19+	0	0	0	0	1	3
F20	0	0	0	1	1	1
F21+	0	0	0	0	0	1
	0	1	5	11	16	29

+ fettlers who did not miss warning shouts other than those which could not produce contralateral responses.

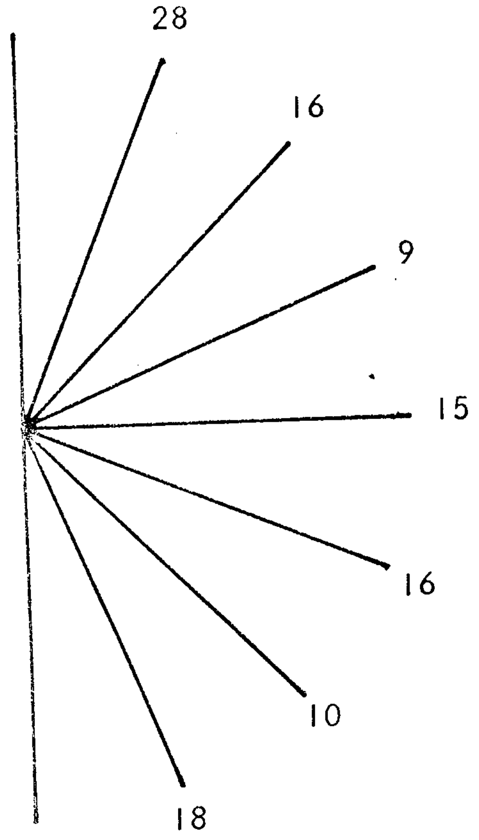
TABLE 20

Contralateral Responses to Nine Warning Shouts, One from Each of the Nine Directions for the Eighteen Office Employees

Subject	Background Noise Level 75dB(A)			Background Noise Level 95dB(A)		
	Unoccluded	Earplugs	Earmuffs	Unoccluded	Earplugs	Earmuffs
01	0	0	0	0	0	1
02	0	0	0	1	0	1
03	0	0	0	0	0	3
04	0	0	0	0	0	0
05	0	0	0	0	0	3
06	0	0	0	0	1	4
07	0	0	0	0	0	1
08	0	0	0	0	0	1
09	0	0	0	0	0	1
010	0	0	0	1	1	3
011	0	0	4	0	0	2
012	0	0	0	0	0	2
013	0	0	0	2	1	0
014	0	0	0	3	0	4
015	0	0	0	0	0	0
016	0	0	0	0	2	1
017	0	0	0	0	0	2
018	0	0	0	1	0	1
	0	0	4	11	5	30

FIGURE 28

Distribution*of Contralateral Responses to the Warning Shouts: Responses for Office Employees and Fettlers Combined for all Three Listening Conditions in Both Background Noise Levels



* indicates direction from which shout originated

TABLE 21

Number of Errors Greater than Thirty Degrees made by Each Subject: Office Employee Subject Group in Low and High Background Noise Levels

Subject	Background Noise Level 75dB(A) Unoccluded	Earplugs	Earmuffs	Background Noise Level 95dB(A) Unoccluded	Earplugs	Earmuffs
01	5	5	4	6	8	6
02	1	6	4	4	5	6
03	3	3	2	7	4	9
04	4	5	7	6	4	7
05	3	4	2	5	4	6
06	5	5	6	5	6	7
07	3	0	4	3	4	6
08	3	3	6	4	7	6
09	1	3	5	6	4	5
010	3	4	7	6	4	7
011	3	4	6	5	6	7
012	1	2	2	5	3	7
013	2	3	5	6	5	4
014	2	5	5	7	3	7
015	3	3	4	5	7	7
016	2	6	4	4	7	7
017	2	3	2	5	5	5
018	4	4	2	7	4	5
Total	50	68	77	96	90	114
Mean	2.8	3.8	4.3	5.3	5.0	6.3

Each cell represents results from nine stimulus presentations, one from each of the nine stimulus positions.

TABLE 22

Number of Errors Greater than Thirty Degrees made by Each Subject: Fettler Subject Group in Low and High Background Noise Levels

Subject	Background Noise Level 75dB(A)			Background Noise Level 95dB(A)		
	Unoccluded	Earplugs	Earmuffs	Unoccluded	Earplugs	Earmuffs
F1	3	3	1	5	6	4
F2	2	4	4	5	3	4
F3	2	4	7	6	5	7
F4	4	5	4	5	5	4
F5	2	5	4	5	5	4
F6	3	4	3	5	6	5
F7	1	4	5	6	2	7
F8	4	4	5	5	7	5
F9	4	1	3	4	3	4
F10	3	2	4	7	6	7
F11	3	4	2	4	5	3
F12	2	2	1	5	4	6
F13	5	4	6	6	6	7
F14	4	6	4	6	7	4
F15	3	4	5	7	7	6
F16	3	4	5	7	8	9
F17	6	4	8	6	7	9
F18	4	4	5	7	5	8
F19	4	5	3	5	5	6
F20	4	5	7	8	6	8
F21	5	5	4	4	4	7
Total	71	81	89	119	115	129
Mean	3.4	3.9	4.2	5.7	5.5	6.1

TABLE 23

A Summary of Results from Localisation Experiments in Which Both Ears have been Occluded

	Experimental Conditions	Percentage of Total Responses Judged Correctly (ie error less than 30°)			Percentage loss in Localisation ability*	
		Unoccluded	Earplugs	Earmuffs	Earplugs	Earmuffs
Atherley & Noble (1970)	1kHz pure tones in anechoic conditions	76	-	50		34
Atherley & Else (1971)	1kHz pure tones in reverberant conditions	55	-	40		27
Noble & Russell (1972)	1kHz pure tones in anechoic conditions	49	48	38	0	22
Noble & Russell (1972)	White noise in anechoic conditions	95	83	68	13	28
Else Experiment 1	Impact noise in anechoic conditions	81	83	52	-2	36

cont'd

Table 23 cont'd

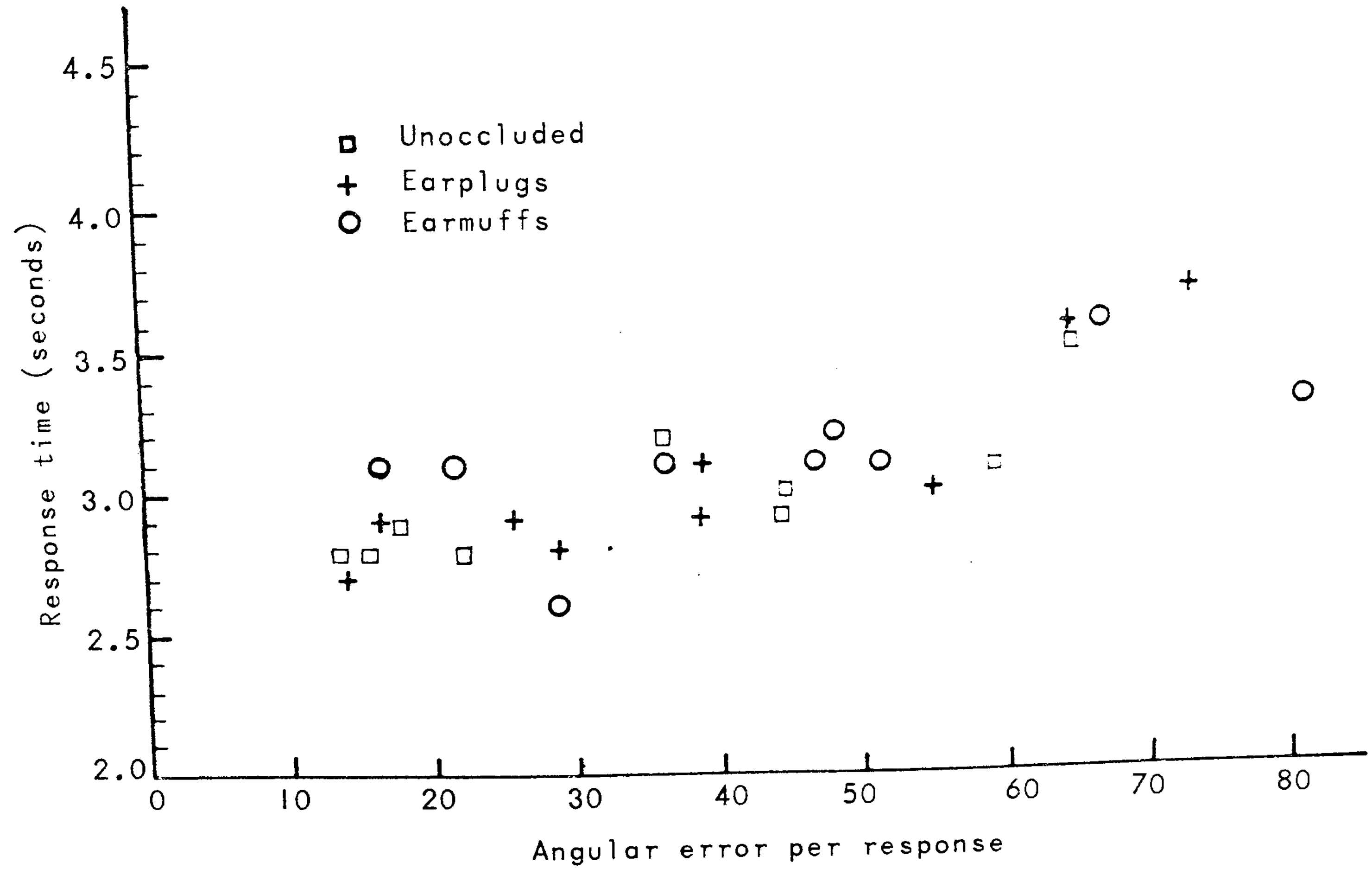
Summary of Results from Localisation Experiments (cont'd)

			Percentage of Total Responses Judged Correctly (ie error less than 30°)			Percentage loss in Localisation ability*	
			Unoccluded	Earplugs	Earmuffs	Earplugs	Earmuffs
Else Experiment 2	Impact noise in anechoic conditions in presence of white noise		65	72	53	-11	18
Else	Warning shouts semi-anechoic conditions in presence of 75dB(A) pink noise	Fettlers	63	58	53	8	16
		Office Employees	69	57	53	17	23
	Warning shouts semi-anechoic conditions in presence of 95dB(A) pink noise	Fettlers	37	39	33	-5	11
		Office Employees	41	44	30	-7	27

* Defined as the reduction in correct responses as a percentage of the number of correct responses in the unoccluded condition.

FIGURE 29

Comparison Between Average Angular Error per Response and Average Response Time for Each of the Nine Stimulus Directions - Office Employees in 75dB(A) Background Noise Level

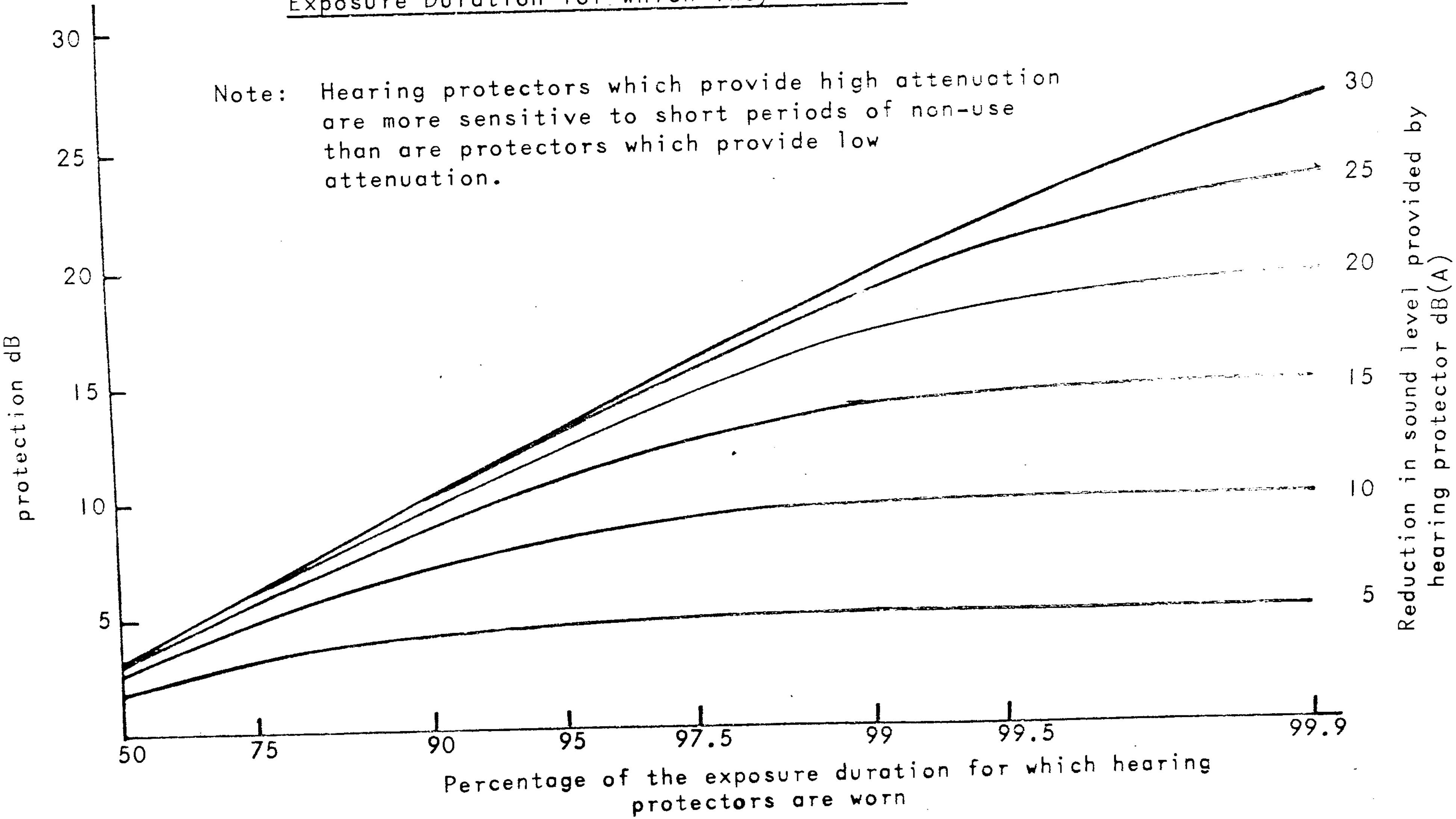


CHAPTER SIX

Figures 30 - 32

FIGURE 30*

Protection Provided by Hearing Protectors as a Function of the Reduction in Sound Level they provide and the Percentage of the Exposure Duration for which They are Worn



Note: Hearing protectors which provide high attenuation are more sensitive to short periods of non-use than are protectors which provide low attenuation.

---

* reproduced from Figure 6.

FIGURE 31

The Reduction in Equivalent-Continuous Sound Level (Protection) Provided by Glass Down Earplugs Against a Sample of 2640 Industrial Noise Spectra: Calculations based on Lower Quartile Attenuation data from Appendix II

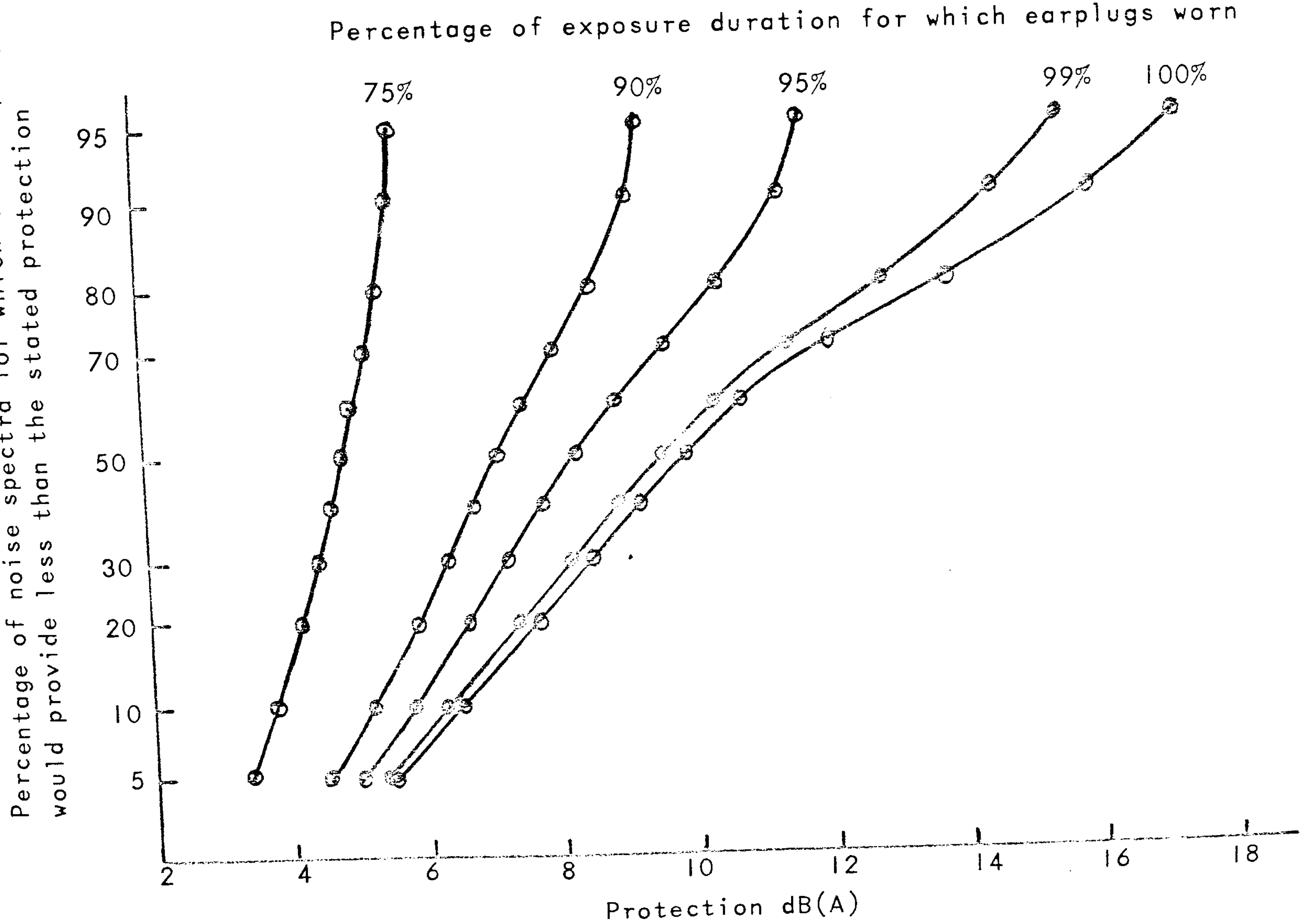


FIGURE 32

Comparison of New Seal from Amplivox Auralguard II Earmuff with one that had been used for Three Months in Foundry

APPENDIX X

THE DEGREE OF PROTECTION AFFORDED BY HEARING PROTECTORS IN INDUSTRIAL NOISE: VARIATIONS WITH NOISE SPECTRA AND WITH PEOPLE

HEARING PROTECTORS

11th October, 1971.

THE DEGREE OF PROTECTION AFFORDED BY HEARING PROTECTORS IN INDUSTRIAL NOISE: VARIATIONS WITH NOISE SPECTRA AND WITH PEOPLE

D. Else, University of Aston in Birmingham.

Ann. occup. Hyg. Vol. 16, pp. 81–83. Pergamon Press 1973. Printed in Great Britain

A NOTE ON THE PROTECTION AFFORDED BY HEARING PROTECTORS—IMPLICATIONS OF THE ENERGY PRINCIPLE

D. Else

University of Aston in Birmingham