# HEARING PROTECTORS

## A dilemma involving acoustics and personal safety

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by

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## SUMMARY

This thesis is concerned with the optimising of hearing protector selection.

A computer model was used to estimate the reduction in noise exposure and risk of occupational deafness provided by the wearing of hearing protectors in industrial noise spectra. The model was used to show that low attenuation hearing protectors can provide greater protection than high attenuation protectors if the high attenuation protectors are not worn for the total duration of noise exposure; or not used by a small proportion of the population.

The model was also used to show that high attenuation protectors will not necessarily provide significantly greater reduction in risk than low attenuation protectors if the population has been exposed to the noise for many years prior to the provision of hearing protectors.

The effects of earplugs and earmuffs on the localisation of sounds were studied to determine whether high attenuation earmuffs are likely to have greater potential than the lower attenuation earplugs for affecting personal safety. Laboratory studies and experiments at a foundry with normal-hearing office employees and noise-exposed foundrymen who had some experience of wearing hearing protectors showed that although earplugs reduced the ability of the wearer to determine the direction of warning sounds, earmuffs produced more total angular error and more confusions between left and right.

It is concluded from the research findings thatthe key to the selection of hearing protectors is to be found in the provision of hearing protectors that can be worn for a very high percentage of the exposure time by a high percentage of the exposed population with the minimum effect on the personal safety of the wearers - the attenuation provided by the protection should be adequate but not a maximum value.

hearing protectors
selection
localisation
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# CHAPTER ONE

# INTRODUCTION

Habitual exposure to high levels of noise causes hearing loss - this has been known since before the turn of this century. Hearing protectors in the form of earplugs were in use in the last century (Barr, 1886). By 1908 the use of hearing protectors was being advocated by Legge in his annual report to the Chief Inspector of Factories.

Hearing protectors have continued to play an important part in industry's attempts to combat occupational deafness. The survey of action taken in 100 factories, undertaken by HM Factory Inspectorate during 1973 and 1974 (Department of Employment, 1975) showed that 80 percent had provided hearing protectors for some members of their workforce; 54 percent of the companies claimed to have made improvements to reduce noise levels.

The importance of the role played by hearing protectors has lead to much research centred on the study of attenuation: the design of hearing protectors to achieve high attenuation; the design of test methods to measure the attenuation provided by them; and the formulation of selection methods to ensure that hearing protectors of sufficiently high attenuation may be chosen to reduce noise levels to the current recommended limits.

Hearing protectors which provide high attenuation are now available and many countries have developed standard methods for testing the attenuation provided by hearing protectors for sounds of different frequencies within the audible frequency range.

The selection methods which have been devised provide methods for estimating the attenuation provided by hearing protectors in different noise spectra. The selection methods attempt to take into account that hearing protectors do not provide the same attenuation for all users or for the same user on different occasions.

Current selection methods aim to select hearing protectors that will reduce the instantaneous sound levels below recommended limits but they do not specify by how much the sound levels at the wearers' ears should be reduced below the limits. This can often lead to the selection of hearing protectors of high attenuation for noise exposures which only slightly exceed the recommended limits. For example, a hearing protector which reduces the sound level by 25dB(A) might be chosen for a person exposed to 93dB(A) for eight hours per day or for a person exposed to 110dB(A) for ten minutes per day.

Although much research effort has gone into the designing,

testing and selecting of hearing protectors, the latest estimate of hearing protector usage reported by the Chief Inspector of Factories is alarmingly low. Overall, less than 12 percent of the hearing protectors that had been selected and provided in 100 factories were being worn when the factory inspectors visited the factories during 1973 and 1974 (Department of Employment, 1975). It is perhaps as a result of this low usage that the Industrial Health Advisory Sub-Committee on Noise has recommended that legislation should contain an obligation on employees to wear hearing protection (Health and Safety Executive, 1975).

Discomfort is undoubtedly a major contributory factor to the low usage of hearing protectors. Placing a legal obligation on the wearer may, or may not, outweigh the discomfort, but discomfort is not the only reason for the alarmingly low usage. Many potential wearers of hearing protectors express concern that the protectors will put them in greater danger, eg. Sugden (1967) reported that some foundrymen who had worn hearing protectors gave this as their reason for ceasing to use protectors. Other authors have expressed concern that hearing protectors could, in some circumstances, present a further hazard to the wearer, eg. Coles and Rice (1965), Dunn (1970), Burns (1973). Atherley and Noble (1970) found evidence from their laboratory study

of localisation to support the claims made by foundrymen that earmuffs reduced their ability to determine the direction of sounds. Atherley and Noble concluded that earmuffs should be viewed with suspicion from the point of view of safety in industry.

The person charged with the responsibility for selecting hearing protectors may therefore be faced with a dilemma. If he chooses the hearing protectors affording the highest attenuation - earmuffs - he may run the risk of affecting directional hearing and perhaps put the wearers in greater danger of other physical injury. But if he chooses earplugs, which may or may not affect directional hearing, he will have to accept a lower degree of attenuation.

The present work has the primary objective of testing the thesis that: hearing protectors should be chosen to provide the optimum* attenuation rather than the maximum attenuation of noise. In meeting the primary objective two secondary objectives have been tackled in the research:

(i) To establish whether high attenuation hearing protectors necessarily provide greater protection from the risk of occupational deafness than lower attenuation hearing protectors

*where optimum is defined as the greatest reduction in the risk of occupational deafness that can be achieved with the least detrimental effect on the safety of the wearer.

(ii) To determine whether high attenuation hearing protectors are likely to produce more deleterious effects than lower attenuation hearing protectors.

The reductions in risk of occupational deafness afforded by hearing protectors are investigated in Chapter 2. The effects of earmuffs and earplugs on directional hearing are compared under laboratory conditions in Chapter 3; the comparisons are extended to more realistic conditions at a foundry in Chapter 4. Evidence, other than that based on localisation, that hearing protectors may adversely affect the safety of the wearer is presented in Chapter 5. Optimising the selection of hearing protectors to reduce the risk of occupational deafness with the minimum increase of other dangers is discussed in Chapter 6.

# CHAPTER TWO

# REDUCING THE RISK OF OCCUPATIONAL DEAFNESS FROM EXPOSURE TO NOISE

## Introduction

Earmuffs generally provide greater reductions in A-weighted sound levels than can be provided by earplugs. However, it has not been shown that the high reductions in sound level provided by earmuffs are always necessary.

Hearing protectors are provided to reduce the risk of occupational deafness. The amount by which the hearing protectors reduce the risk must be central to any decision to select earmuffs rather than earplugs, or high attenuation earmuffs rather than low attenuation earmuffs. It is, therefore, necessary to develop a method for calculating the residual risk of occupational deafness for wearers of hearing protectors.

The hearing protector selection procedures which have been discussed in Appendix I all assume that the hearing protectors will be worn. In practice, hearing protectors may not be worn during part of the noise exposure. It may be possible to ensure high usage with the most comfortable protectors - but these may not be the protectors which provide the highest attenuation of the noise. A low attenuation hearing protector worn for the full duration of noise exposure might

provide greater reduction in the risk of occupational deafness than would be provided by high attenuation hearing protectors worn for a small proportion of the duration of exposure. The trading relations between hearing protector attenuation and degree of usage must therefore be explored.

Hearing protectors are often provided for people who have already been exposed to noise for the major part of their working lives. Hearing protectors will reduce the noise that is received over the latter years of the working lifetime, but they will not greatly reduce the total noise dose received over the lifetime. In such a situation, the question arises whether the wearing of high attenuation hearing protectors such as earmuffs will provide substantially greater reductions in risk than could be provided by the wearing of low attenuation hearing protectors such as earplugs.

The incidence of occupational deafness will be reduced as a consequence of the reduction in risk provided by hearing protectors. But ultimately the incidence of occupational deafness will depend on the number of people who do not wear hearing protectors. The consequences, therefore, of a proportion of the population not wearing any form of hearing protectors should also be studied.

## The Risk of Hearing Loss Resulting from Unprotected Exposure to Noise

Robinson (1968) has shown that frequency weighted sound

energy is an appropriate parameter for the prediction of injury to hearing 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. Atherley and Martin (1971) found that the energy rule appeared to hold for impact noise which consisted of short bursts of relatively high energy.

Burns and Robinson (1970), Robinson (1971) and Robinson and Shipton (1973) have described the relations between A-weighted noise dose and the hearing levels to be expected in various percentages of the exposed population at various ages. It is therefore possible to estimate at any frequency the hearing levels for centiles of an exposed otologically normal population from the A-weighted noise dose to which the population has been exposed. The percentage of an otologically normal population likely to exceed a particular hearing level after exposure for a known duration to a given noise level can therefore be calculated.

The effects of ageing and the effects of noise exposure cannot be separated by measurements of hearing; the hearing levels predicted by Robinson's equations are the result of both ageing and noise exposure. Noise-induced hearing loss cannot be isolated by measurement, except in young people for whom ageing has not had an effect. The presumed noise-induced hearing loss can be derived by substituting a correction for

presbycusis, but in view of the large variations in published experimental presbycusis data (Robinson, 1971) no attempt will be made in this analysis to isolate the noise-induced component of hearing loss from the total hearing loss.

The problems associated with defining occupational deafness and with estimating the risk of suffering occupational deafness from exposure to noise have been discussed by Robinson (1971), Burns (1973) and Robinson and Shipton (1973). A mean hearing level of 25 decibels for the average of 500Hz, 1000Hz and 2000Hz ($25 dBHL_{\overline{0.512}}$) has been used as a criterion for the beginning of impairment for speech for many years by the American Academy of Ophthalmology and Otolaryngology (AAOO, 1964) and by the International Organisation for Standardisation (1971). Hearing handicap for compensation purposes in the U.S.A. has been interpreted as beginning at a mean hearing level of 26 decibels for the average of 500Hz, 1000Hz and 2000Hz (Davis, 1970). The limit of 'moderate handicap' (frequent difficulty with normal speech) is assumed to be $40 dBHL_{\overline{0.512}}$ by the American Academy of Ophthalmology and Otolaryngology (Burns, 1973).

The Industrial Injuries Advisory Council found it necessary to define a level of 'severe hearing loss' beyond which industrial injuries benefit would be allowed (Department of Health and Social Security, 1973). They chose to adopt a mean hearing level of 50dB, being the average of 1000Hz,

2000Hz and 3000Hz and this has been incorporated within the scheme for compensating the sufferers from very severe occupational deafness.

The percentages of an otologically normal population that would be likely to exceed the various occupational deafness criteria after a working lifetime of exposure to noise levels in the range 80dB(A) to 120dB(A) are illustrated in Figure 1. In each case the exposure is assumed to have started in a person's seventeenth year and finished in the sixty-sixth year. The risk curves have been calculated by the methods described by Robinson and Shipton (1973).

As can be seen from Figure 1, approximately 16 percent of the population would be expected to have hearing levels in excess of $25\text{dBHL}_{\overline{0.512}}$ after the 49 years of exposure to a noise level of 90dB(A) for eight hours per day, five days per week and 50 weeks per year. The same duration of exposure to 115dB(A) would be expected to result in hearing levels in excess of $25\text{dBHL}_{\overline{0.512}}$ for more than 90 percent of the population.

The British Occupational Hygiene Standard for Wide-Band Noise (1971) was based on the energy rule. It provided a system for estimating the proportion of a noise exposed population that would be likely to exceed an arbitary standard of handicap based upon symptoms of occupational deafness following noise exposure. The Standard recommended a limit

of 90dB(A) for habitual daily exposure; the Standard estimated that exposure to a level of 90dB(A), forty hours per week, forty-eight weeks per year for thirty working years, would result in handicap for less than one percent of the exposed population.

The Department of Employment issued their Code of Practice in 1972 which was also based on the energy rule. In selecting 90dB(A) as the recommended limit for eight-hour daily exposure to noise, the Industrial Health Advisory Committee whose sub-committee on noise was responsible for producing the Code, were aware of the small but definite residual risk from a working lifetime of exposure to 90dB(A) (Robinson and Shipton, 1973).

The International Organisation for Standardisation Recommendation R.1999 (1971) was based on the energy rule, and also provided a system for estimating the proportion of a population likely to exceed $25\text{dBHL}_{\overline{0.512}}$ after a lifetime of exposure to noise. However, the risk estimates were not based on an otologically normal population, but more in the nature of a random sample from the industrial population (Robinson and Shipton, 1973).

The use of a 90dB(A) limit for eight-hour daily exposure to noise implies the acceptance of the residual risk associated with exposure to 90dB(A) for a working lifetime.

The residual risk is described in various ways in Table I from which it can be seen that the estimated residual risk varies considerably depending on: the definition of what constitutes occupational deafness; whether the population is assumed otologically normal, or a more random selection including pathology; and to a much lesser extent the length of the working lifetime.

## A Computer Model for Estimating the Residual Risk of Hearing Loss when Hearing Protectors are Worn

When hearing protectors are worn by a population, some people will receive greater reductions in A-weighted sound level than will others. The members of a population will not be exposed to a uniform risk of hearing loss, because some people will be exposed to higher noise levels than others. However, the overall residual risk for the population will be the sum of the individual risks. The residual risk will be the percentage of the population of wearers of hearing protectors that would be expected to exhibit hearing losses at the end of a working lifetime. Obviously there can be little justification for attempting to reduce the residual risk for populations wearing hearing protectors below the residual risks accepted for unprotected exposure to noise (ie. those given in Table I).

A computer model has been developed to estimate the residual risks when hearing protectors are provided for a

population exposed to noise. The model is described in detail in Appendix III; a summary of the model is given below and a flow chart summary of the computer model is given in Figure 2.

The A-weighted sound level at the occluded ear is calculated for each centile of the population wearing hearing protectors; this is calculated from the octave band sound levels of the noise and the mean and standard deviations of the hearing protector attenuation data. The distribution of attenuation for the hearing protector is assumed to be normal - an assumption which has been tested in Appendix I.

The method of calculating the A-weighted sound level has been shown to involve only slight errors for centiles below the lower quartile (Appendix I). The reduction in A-weighted sound level afforded to the upper quartile is over-estimated by the method. However, hearing protectors are usually chosen to reduce the noise level to 90dB(A) for at least 75 percent of wearers. Those persons receiving high reductions in noise level (the upper centiles in the attenuation distribution) will be exposed to levels below 90dB(A) and from Figure 1 it can be seen that the risk curve for $25\text{dBHL}\frac{}{0.512}$ below 90dB(A) has only a slight gradient and the error in risk resulting from errors in A-weighted sound level should therefore be small.

In the computer model the residual risk for each centile of the population wearing hearing protectors is calculated from cubic approximations to the risk curves of Figure 1. The residual risk for the whole population wearing hearing protectors is then obtained by integrating the risks over all centiles.

The occupational deafness criterion of $25dBHL_{\overline{0.512}}$ has been incorporated in the computer model although any of the other criteria could have been used.

The accuracy of the residual risk estimates provided by the computer model cannot be defined because they are computed from risk curves for which no confidence limits are available. The computer model can be used to compare the hearing protector selection criteria and to explore relations between the reduction in residual risk and the attenuation provided by different hearing protectors.

## Relations Between Residual Risk and Attenuation

The computer model has been used to calculate the residual risk of exceeding $25dBHL_{\overline{0.512}}$ for people who have worn hearing protectors for a working lifetime of exposure to 120dB(A). The residual risk of exceeding $25dBHL_{\overline{0.512}}$ was found to be approximately 19 percent for the case of hearing protectors which provide a mean reduction of 30dB(A) with a standard deviation of 5dB(A). The computer model has also been

applied to all combinations of hearing protector A-weighted reductions from 5dB(A) to 30dB(A) and noise levels 85dB(A) to 120dB(A). The calculated residual risks are displayed in Figure 3.

Clearly, hearing protectors can be used to reduce the residual risk to the level accepted for unprotected ears (ie. 16 percent risk of $25dBHL_{\overline{0.512}}$) provided that a hearing protector of sufficiently high attenuation is used.

Current criteria for selecting hearing protectors attempt to reduce the A-weighted sound level to 90dB(A) when the hearing protectors are worn. The Department of Employment's Code of Practice (1972) requires the use of lower quartile attenuation data or the mean minus the standard deviation of the data in the calculations. The Australian Standards Association's 1972 Draft Code of Practice requires the use of the mean minus one and a half standard deviations of the data, whilst in the U.S.A. it is likely that the mean minus twice the standard deviation will be required (Shaw, 1976).

The residual risk of exceeding $25dBHL_{\overline{0.512}}$ that could be expected to result from wearing hearing protectors chosen according to various criteria is detailed in Table 2. The residual risk that would result from using mean attenuation data is also shown in Table 2. The selection criteria appear to reduce the risk of occupational deafness to below the level

accepted for unprotected exposure. Clearly, the use of mean attenuation data in the calculation would not result in 50 percent of the wearers being 'unprotected' from occupational deafness.

In Figure 4 the residual risks of $25dBHL_{\overline{0.512}}$ are illustrated for noise levels 85dB(A) to 120dB(A) and hearing protectors of mean A-weighted reductions 5dB(A) to 30dB(A); but the distributions of attenuation are assumed to be wider than used for previous calculations (ie. standard deviations of 10dB(A) have been used). The residual risks that could be expected to result from wearing hearing protectors chosen according to the various criteria are illustrated in Table 2, from which it can be seen that the residual risk is affected only marginally by the larger variance in hearing protector attenuation data.

## The Effects which Result from Hearing Protectors Not Being Worn for the Total Duration of Exposure

The energy rule has formed the basis of the Codes and Standards produced by the British Occupational Hygiene Society (1971), the International Organisation for Standardisation (1971), the Department of Employment (1972) and others. All of these utilise the concept of equivalent-continuous sound level (ECSL) in the predicting of injury from non-continuous noise and non-continuous noise-exposures. The ECSL can be defined as the level of continuous sound, in dB(A), which in

the course of an eight-hour working day would cause the same A-weighted sound energy to be received as that due to the actual noise over the actual working day.

The Department of Employment's Code of Practice specifies an ECSL of 90dB(A) as the limit which should not be exceeded in an attempt to limit the total A-weighted noise dose received over any one day. The British Occupational Hygiene Society Standard utilises ECSL, but recommends limiting the noise dose received over the working lifetime.

Clearly the ultimate aim of both Standards is to limit the amount of noise dose received by people during their working lifetimes.

The A-weighted noise dose received over a working lifetime will be given by:

$$Q = \int_0^T I_{(t)}\, dt$$

Equation 1

where Q is the A-weighted noise dose received cumulatively during a working lifetime of T years, where $I_{(t)}$ denotes the A-weighted sound intensity at time t.

Robinson (1968) proposed the term 'noise immission' to describe the total A-weighted noise dose that has been received by a person who has been exposed to noise; and 'noise immission level' to describe a logarithmic measure of the total noise dose.

A reference exposure duration of $T_o$ years, and a reference intensity $I_o W/m^2$ can be defined such that the noise immission level, E, will be given by:

$$E = Leq + 10 \log \frac{T}{T_o} \qquad \text{Equation 2}$$

(Equation 2 assumes that the ECSL over one working day is a reliable estimate of the noise energy received over all other days of the working lifetime of exposure. The reference duration $T_o$ is usually one year consisting of either 48 or 50 working weeks, each of 40 hours' duration.)

where Leq is the ECSL defined by:

$$Leq = 10 \log \frac{1}{8} \int_0^{\tau} \frac{I(t)}{I_o} \, dt \qquad \text{Equation 3}$$

where $\tau$ is the total daily exposure duration in hours.

Consider the case of a person who is provided with hearing protectors, but does not wear them for the total time for which he is exposed to noise. Thus the total noise dose he receives over his lifetime can be divided into two components $Q_1$ the energy received whilst the protectors are worn and $Q_2$ the energy received whilst the protectors are not worn. The total energy received by the person provided with hearing protectors, $Q_p$, will be the sum of $Q_1$ and $Q_2$, that is:

$$Q_p = Q_1 + Q_2 \qquad \text{Equation 4}$$

which can be expressed in noise immission levels:

$$E_p = 10 \log \left[ 10^{\frac{E_{p1}}{10}} + 10^{\frac{E_{p2}}{10}} \right] \qquad \text{Equation 5}$$

where $E_p$ is the noise immission level for the total exposure

to noise over the working lifetime, $E_{p1}$ is the noise immission level for the duration of the exposure during which the hearing protectors are worn, and $E_{p2}$ is the noise immission level for the duration of exposure during which the hearing protectors are not worn.

The noise immission level for the period during which the protectors are worn will be given by:

$$E_{p1} = 10 \log \left[ 10^{\left( \log \sum_x 10^{\frac{L_x - W_x - A_x}{10}} - \log \frac{100}{V} \right)} \right] + 10 \log \frac{T}{T_o}$$

Equation 6

$L_x$ is the octave band sound level centred at x hertz; where exposure is for a period other than 8 hours, $L_x$ is the equivalent octave band sound level which would deliver the same amount of unweighted energy; $W_x$ is the A-weighting correction at x hertz; $A_x$ is the attenuation provided by the hearing protector to noise in that octave band; and V is the percentage of the exposure duration for which the hearing protectors are worn.

The noise immission level for the period during which the hearing protectors are not worn will be given by:

$$E_{p2} = 10 \log \left[ 10^{\left( \frac{L_{eq}}{10} - \log \frac{100}{100 - V} \right)} \right] + 10 \log \frac{T}{T_o}$$

Equation 7

If the protection (P) afforded by the wearing of the hearing protectors is defined as the reduction in the noise immission

level that is achieved by the wearing of hearing protectors, then:

$$P = E - E_p \qquad \text{Equation 8}$$

from which:

$$P = L_{eq} - 10\log\left[10^{\left(\frac{L_{eq}}{10} - \log\frac{100}{100-V}\right)} + 10^{\left(\log\sum_x 10^{\frac{L_x - W_x - A_x}{10}} - \log\frac{100}{V}\right)}\right]$$

Equation 9

This will be numerically equal to the reduction in ECSL afforded by the wearing of the hearing protectors if the hearing protectors are provided and used throughout the lifetime of exposure to noise.

I have previously shown (Else, 1973) that for a hearing protector with theoretically infinite attenuation at all frequencies, equation 9 reduces to:

$$P_{max} = 10 \log \frac{100}{100-V} \qquad \text{Equation 10}$$

where $P_{max}$ is the maximum reduction in noise immission level or ECSL that can be achieved by wearing the infinite hearing protector for V percent of the exposure duration. Figure 5 shows the relation between $P_{max}$ and the percentage of the exposure time for which the hearing protector is worn.

It is clear from Figure 5 that a hearing protector with infinite attenuation would give no more than six decibels of protection to any person if it was worn for less than 75 percent of the exposure duration. Similarly, if it was required to protect a man exposed in an ECSL of 120dB(A), even an

infinite hearing protector would have to be worn for at least 99.9 percent of the exposure duration.

When account is also taken of the noise energy received whilst the hearing protector is worn, the protection calculated from Equation 9 will be less than is predicted for the hearing protector with infinite attenuation.

The relation between protection (P) and the percentage of the time for which the protector is worn (V) is shown in Figure 6 for hearing protectors providing between 5dB(A) and 30dB(A) reduction in A-weighted sound levels. If a hearing protector is not worn for the full duration of an exposure then the same protection can be achieved with a hearing protector which provides less instantaneous reduction in sound level, provided that it is worn for a sufficiently high percentage of the exposure duration.

If hearing protectors are worn less than 75 percent of the exposure duration, there will be less than 5dB(A) difference between the protection afforded by a hearing protector which reduces the sound level by 30dB(A) and one which reduces the sound level by only 5dB(A). However, the differences between the protection provided by different protectors become more important when the protectors are worn for the whole or nearly the whole duration of exposure.

Therefore, although current standards provide procedures

for selecting hearing protectors to reduce the A-weighted noise level to 90dB(A) or less, it has been shown that unless the hearing protectors are worn for a very high proportion of the noise exposure, the wearer may nevertheless be exposed to more than the recommended daily noise dose. When the time worn is taken into account, it can be shown that low attenuation hearing protectors can reduce the noise dose by as much or by more than high attenuation hearing protectors.

The ultimate aim of providing hearing protectors is the reduction of the total noise dose received by the ears throughout the working lifetime. It is therefore important to investigate the amount by which a person's total immission of noise dose can be reduced by providing hearing protectors part-way through the noise exposure. Equation 9 has been used to calculate the reduction in noise immission level provided by the wearing of hearing protectors which reduce the sound level by between 5dB(A) and 30dB(A). The calculations have been made assuming that the total duration of exposure is 49 years and that the hearing protectors have been provided part-way through the exposure. The resultant reductions in noise immission level are illustrated in Figure 7.

If a person has already been exposed to the noise for the major part of his working lifetime, only slight reductions

in noise immission level can be achieved by wearing hearing protectors for the rest of the exposure duration. Attempts to reduce the total noise dose received over the working lifetime will only reduce the noise dose immitted in the latter years and this noise dose may not be a large proportion of the total noise dose that the person receives during the whole working lifetime.

Obviously there cannot be large differences between the reductions in noise immission level provided by earplugs or by earmuffs unless these are provided very early in the noise exposure and worn consistently throughout the working lifetime of exposure to noise.

If a person has previously been exposed for 25 years and then wears earmuffs that reduce the noise level by 30dB(A) for the remaining 24 years, he will only reduce his total noise immission level by three decibels; this is only half a decibel more than the reduction in immission level that would be provided by wearing earplugs which only reduce the sound level by 10dB(A). The differences between the reductions possible for earplugs and earmuffs will be more substantial if a person has previously been exposed for only six months; when the wearing of earmuffs which reduce the noise level by 30dB(A) may reduce the total noise immission level by nine decibels more than will the wearing of earplugs which reduce

the noise level by 10dB(A). Of course, this does assume that the hearing protectors are worn at all times during the period of the working lifetime for which the hearing protectors are provided. If they are not worn for a very high proportion of this period, there will be much smaller differences between the effects of earmuffs and earplugs.

Figure 7 shows that the earlier hearing protectors are provided during a lifetime of noise exposure, the greater is the possible reduction in total noise immission level.

The Relations Between Residual Risk, Attenuation and the Percentage of the Exposure Duration for Which They are Worn

The computer model (Appendix III) can be used to estimate the risk of exceeding a hearing level criterion (eg. $25dBHL_{\overline{0.512}}$) for a population of persons wearing hearing protectors; the residual risk can be estimated on the assumption that the protectors are worn 100 percent of the exposure duration or for lower percentages of the total duration of exposure.

The model has been used to estimate the residual risk for a population wearing hearing protectors in a noise level of 95dB(A) for a working lifetime. Each curve in Figure 8 describes the percentage of the population that would be likely to exceed $25dBHL_{\overline{0.512}}$ if they were to wear protectors for various percentages of the exposure duration. The residual risks are shown for hearing protectors which reduce

the sound level by between 5dB(A) and 35dB(A); the standard deviations for the hearing protector attenuations are constant and equal 5dB(A).

In Figure 9 are shown the residual risks that would be expected if the same hearing protectors are worn for a working lifetime in a noise level of 120dB(A). Again, the hearing protectors' attenuation has little effect on the residual risk unless the protectors are worn for a high percentage of the exposure duration.

Hearing protector attenuation can be seen to have little effect on the residual risk unless the hearing protectors are worn for a high percentage of the exposure duration. The risk can be reduced either by low attenuation hearing protectors worn for a high percentage of the time, or by higher attenuation hearing protectors worn for a slightly lower percentage of the time.

It has been assumed in the previous sections that the whole of the population exposed to high noise levels has been provided with hearing protectors and wear them, but in practice it is likely that some people at risk will choose not to wear the hearing protectors that are provided. Obviously the incidence of occupational deafness will be greater if some people do not wear the hearing protectors.

In Figure 10 the effect of providing a population exposed to 105dB(A) with earplugs (mean A-weighted reduction of 20dB(A) : standard deviation 5dB(A)) is compared with the effect of providing them with earmuffs (mean attenuation 35dB(A) : standard deviation 5dB(A)). Residual risk curves are shown for the condition where the whole of the exposed population wears the earplugs, or earmuffs, and for the conditions where only: 90 percent, 75 percent and 50 percent wear the earplugs or earmuffs.

Comparison of the residual risk curves for earplugs and earmuffs clearly shows that the providing of earplugs will decrease the incidence of occupational deafness more than the providing of earmuffs if the earplugs are rejected by considerably fewer people than reject earmuffs.

Summary - The Importance of Achieving a High Degree of Utilisation of Hearing Protectors

Hearing protectors are provided for populations exposed to noise in an attempt to reduce the incidence of occupational deafness.

The hearing protectors are provided for the individual so that the risk of that individual losing hearing will be lessened. The risk to any individual should be no greater than the level of risk that would be accepted for unprotected

exposure to noise.

It has been shown in this chapter that the amount by which the incidence of occupational deafness can be reduced by the provision of hearing protectors depends on:

1. The reduction in noise level that is afforded by the hearing protectors
2. The percentage of the exposure duration for which the hearing protectors are worn
3. The duration for which the persons have been exposed to the noise prior to the introduction of hearing protectors
4. The percentage of the population that do not wear the hearing protectors.

The amount by which the hearing protectors reduce the risks of hearing loss for an individual will, however, be independent of the last of these factors.

The standards and codes which recommend limits for exposure to noise also provide procedures for selecting hearing protectors, but the procedures do not take into account the factors other than attenuation. When account is taken of the other factors it becomes clear that the provision of high attenuation hearing protectors will not in itself necessarily reduce the incidence, or risk, of occupational

deafness by more than will the provision of much lower attenuation hearing protectors.

Obviously, in the majority of instances where hearing protectors are provided in industry, some of the population will have been previously exposed to the noise without protectors. The reduction in the noise immission level, and hence the risk of occupational deafness, for these persons will be less than is predicted by the selection procedures. For populations that have been exposed to the noise for a major part of their working lifetimes, the reduction in risk provided by high attenuation earmuffs will only be slightly greater than the reduction in risk provided by low attenuation earmuffs or earplugs. However, in the case of persons that are new entrants or that have been previously exposed for only a short period, earmuffs may provide much greater reductions in risk than earplugs can provide, unless the noise exposure only slightly exceeds the recommended limits.

## The Degree of Utilisation of Hearing Protectors Achieved in Industry

There are few documented reports of the percentages of populations that wear hearing protectors.

Heijbel (1961) described the system used for providing glass down earplugs for the employees of a Swedish foundry. The promotional campaign was a vast venture including lectures,

audiometry and personal interviews. The first earplugs were provided in 1953; the thousand employees exposed to the noise were questioned in 1959 and 1961 about their use of the earplugs. Between 37 per cent and 48 per cent said that they wore the earplugs at least occasionally. Earmuffs had been largely abandoned at a very early stage because the men liked wearing them even less than the glass down earplugs.

Sugden (1967) reported the initial stages of a campaign to provide glass down earplugs for about 30 men in a small iron foundry. Although acceptance of the earplugs was high at first - some persons even wore them through the lunch break - by the end of six weeks only about 30 per cent of the men were wearing them regularly.

Lob (1971) reported the results of an attempt to provide glass down and other earplugs for the work force in a wire-drawing factory in Switzerland. The scheme appears to have been applied with enthusiasm; all employees attended lectures about the effects of noise; and audiometry and personal interviews were also used to promote the scheme. However, only 13 out of the 54 employees appeared to wear the protectors on any regular basis - that is no more than 24 per cent of those that had been issued with the protectors.

In the noise survey of British factories undertaken by HM Factory Inspectorate in 1971, a random sample of 100

factories employing a total of 16,048 people were visited (Department of Employment, 1975). Hearing protectors had been provided for 516 of the employees who were exposed to noise levels in excess of 90dB(A), but only 21 of these were wearing the hearing protectors at the time of the survey, ie. only 4 percent of the hearing protectors were being worn.

The Factory Inspectorate re-visited the same 100 factories during 1973 and 1974 to find out what improvements had been made subsequent to the publication of the Department of Employment's Code of Practice which had been issued in 1972. In the follow-up visits, the inspectors were asked to rate the action taken by the companies to provide hearing protection and get it used. In the opinion of the visiting inspectors, the action of 15 percent of the companies could be rated as between 'good' and 'excellent', whilst 50 percent could be rated between 'poor' and 'fair'. In the opinion of the inspectors, 35 percent of the companies had taken 'no action' (Department of Employment, 1975). Although the number employed in the 100 factories had decreased slightly to 14,095, hearing protectors were provided for about twice as many compared with 1971. Of the 1100 employees provided with hearing protectors, only 125 were wearing them at the time of the re-visit, ie. less than 12 percent of the hearing protectors were being worn approximately

two years after the introduction of the code of practice.

The degree of utilisation of hearing protectors will probably be related to the amount of effort given to promotion of the hearing protectors and noise control by the individual company. Individual companies within the survey of 100 factories may have encouraged a much higher percentage of the employees to wear hearing protectors than the average 12 per cent. It is also likely that the utilisation of hearing protectors will have improved since the introduction of the Health and Safety at Work etc. Act, 1974 which has resulted in a much more widespread interest in health and safety amongst employers and employees.

Investigations in the past have not attempted to examine the percentage of the exposure duration for which hearing protectors are worn. For example, the latest survey by HM Factory Inspectorate showed that less than 12 per cent of the hearing protectors were being worn at the time of the visits. This could have been because 12 per cent of the people wore hearing protectors for the whole duration of exposure. Conversely, the whole of the population of wearers may have worn hearing protectors, but each person wore them for only about 12 per cent of the exposure duration. The true position probably existed somewhere between these two extremes - probably closer to the former.

Heijbel (1961) in his study of people wearing glass down earplugs, split his users into two groups: those who said they wore the earplugs all the time, and those who said they occasionally wore them. Between 25 percent and 32 percent of the users of earplugs were classed as occasional users. However, it is not clear whether the full users were, in practice, using the earplugs for the whole of the duration of the noise exposure. My own experience of interviewing men in industry about their use of hearing protectors is that they often consider that they are utilising the protectors fully even though they take them off occasionally and do not wear them for the total duration of their noise exposure.

It is extremely difficult to study the percentage of the exposure for which hearing protectors are worn. Activity sampling (Currie, 1963) at first sight appears to be an appropriate technique for studying the proportions of time spent with hearing protectors on or off. However, the interest lies in very small percentages of the exposure for which the hearing protectors are not worn (of the order of between 0.1 percent and 10 percent). The use of activity sampling to an accuracy of plus or minus one decibel would require a very large number of random samplings - such a high number that the method would be almost indistinguishable from continuous

observation. I have, therefore, used continuous observation to study percentages of the exposure durations for which industrial users of hearing protectors remove their protectors. However, because of the time-consuming nature of continuous observation the study had to be limited to two hearing protector wearers only. In view of this it was vital to use two people who were highly motivated and aware of the need to use the protectors fully. Because of this the hearing protection scheme that the men were drawn from and the history of the scheme has been described in detail in Appendix IV.

The men worked in the fettling shop of a steel foundry. The hearing protection scheme had been introduced, in the form of a pilot scheme, in an area where about twenty people were employed. The small numbers involved made it possible to use a high degree of personal supervision and individual attention.

The two men chosen for the detailed study of the usage of earmuffs were both operators of swing-frame grinding machines. Both men were eager to participate because of their interest in health and safety matters. Both men had worn respiratory protection since its introduction many years before and they appeared to be making full use of the earmuffs.

The two swing-frame grinder operators worked at adjacent machines.

The castings ready for swing-frame grinding were brought by a magnet crane from another part of the fettling shop and were left in a pile within five feet of the swing-frame grinding machines. The operators used an air hoist to move the castings into position beneath the grinding wheel. After each casting had been finished it was moved to another pile about five feet from the swing-frame grinding machines. When the grinding of all the castings was completed the operator would go in search of the crane to arrange for a new pile of unfinished castings to be exchanged for the finished castings. I noticed that the operators generally wore the earmuffs when they were grinding and for most of the time they were moving castings into position. When they were not actively engaged in this part of the work they tended to remove the earmuffs, respirators and eye protection, even though the background noise level was about 90dB(A). For each of the men a study was made of the usage of earmuffs over the course of half a working shift.

The study consisted of estimating the noise dose immitted whilst the hearing protectors were not worn and comparing this to the total noise dose received by the operator.

The total noise dose was estimated using a personal integrating dose meter, the microphone of which was worn at the operator's lapel. The noise dose immitted whilst the protectors were not worn was estimated using a portable noise integrator and hand-held microphone. The microphone was held at head height within 1.5 metres of the operator's position. Whenever the operator removed his earmuffs the integrator and a stop watch were switched on. When the earmuffs were replaced, the ECSL for the period during which the hearing protectors were not worn and the length of the period, were noted. The operators were unaware of my interest in their usage of hearing protectors. A summary of the results from the study for each man is given in Tables 3 and 4.

The men did not remove their hearing protectors when the supervisors or shop steward came to speak to them. However, they did remove their earmuffs when they stopped to clean their eye protectors (which could not be removed without first removing the earmuffs) and when they walked away from their swing-frame grinding machines in search of castings, or someone with whom to talk for a few minutes. During most of the periods when the earmuffs were not worn, the men were exposed to noise levels in excess of 94dB(A). One of the men

also removed his earmuffs for the last fifteen minutes of his shift during which time he was sweeping the area around his machine - in a noise level of approximately 99dB(A) from the other swing-frame grinding machine.

The ECSL to which the men were exposed was estimated from the personal dose meter readings to be between 103dB(A) and 104dB(A). They were provided with earmuffs which should have reduced the ECSL to less than 80dB(A) (on the basis of mean minus one standard deviation attenuation data) if they had worn the earmuffs all the time.

However, the periods during which they did not wear their earmuffs significantly increased their ECSLs to between 86.5dB(A) and 89dB(A).

Tables 3 and 4 show the effect that wearing glass down earplugs continuously would have had.

For one of the operators the ECSL would have been reduced to approximately 91dB(A) from 104dB(A) whilst for the other operator, earplugs would have reduced the exposure from 103dB(A) to 90dB(A).

Clearly the periods during which the earmuffs were not worn - approximately twenty minutes in each half-shift - seriously reduced the effectiveness of the protection provided by the earmuffs. Although the earmuffs were theoretically

capable of providing 24dB(A) protection, in practice they could not have reduced the ECSL by more than 14dB(A) and 18dB(A) respectively.

## Conclusions

In this chapter it has been shown that hearing protectors which provide large reductions in A-weighted sound levels are not always necessary to reduce the risk of occupational deafness to the level accepted for unprotected exposure to noise. Although earmuffs will be required for very high noise levels, there are many industrial noise exposures in which the risk of occupational deafness could be reduced to the acceptable level by either earmuffs or earplugs, and the decision to choose earmuffs or earplugs will have to be made on factors other than their ability to reduce the risk of occupational deafness to an acceptable level.

The reduction in risk provided by earplugs or low attenuation earmuffs, even when they are worn in very high noise levels, can be as large as the reductions provided by high attenuation earmuffs if the latter are worn for a considerably lower percentage of the exposure duration.

Small differences in the attenuation provided by different hearing protectors will be insignificant unless

the protectors are worn for a very high percentage of the duration of exposure.

For populations that have been exposed to noise for many years the wearing of hearing protectors for the remainder of the working lifetime may not greatly reduce the risk of hearing loss. In such cases the reductions in noise dose provided by high attenuation protectors such as earmuffs may not be significantly greater than the reduction provided by low attenuation protectors such as earplugs.

All the points mentioned so far can affect the reduction in risk provided for the individual; this will in turn affect the incidence of occupational deafness. However, the reductions in the incidence of occupational deafness will also be affected by the proportion of the population that does not wear any form of hearing protection. The incidence of occupational deafness may be reduced more by a low attenuation hearing protector that is worn by many people, than by a high attenuation protector that is worn by few people.

Clearly, selecting hearing protectors is not just a simple matter of choosing those which provide the highest attenuation. The likeihood of the device being worn by a high percentage of the exposed population for a very high proportion of the exposure duration must also be considered.

One reason for hearing protectors not being worn is the discomfort that they produce. The method used for selecting hearing protectors should reflect the importance of comfort.

Another reason that has been put forward by foundrymen to explain why they have not used hearing protectors has been the effect which the protectors may have had on their personal safety (Sugden, 1967). Therefore, in the next two Chapters, comparisons are made between low attenuation earplugs and high attenuation earmuffs to determine whether the high attenuation protectors are likely to affect the flow of useful information more than the low attenuation hearing protectors.

# CHAPTER THREE

## THE EFFECTS OF HEARING PROTECTORS ON LOCALISATION ABILITY - A LABORATORY STUDY

It seems that most people during their everyday life are unaware of the extensive use which they make of their ability to determine the direction from which sounds originate. Localisation is used extensively to provide the precursor to the visiual location of 'targets'. We use localisation when swatting flies, crossing roads, locating faults in machinery and in a host of other common everday tasks. Localisation is, of course, also used to focus attention on a person who is speaking, so that use can be made of extra visual cues.

Localisation has been the subject of experimental studies for more than a century and many of the studies have involved monaural occlusion - sometimes with earplugs or earmuffs, or combinations of both. However, the effects of covering both ears with hearing protectors appear not to have been studied prior to the experiment of Atherley and Noble (1970). Their experiment followed reports from workers in foundries that earmuffs reduced the ability to determine the direction of sounds. In recent years I have received many similar reports from other industries.

Atherley and Noble examined the influence of earmuffs on a localisation task in the horizontal plane using a binaural presentation of 1kHz pure tones under anechoic conditions.

Their subjects were fifteen foundry workers, none of whom had ever used hearing protectors. In the experiment, the subject was surrounded by six loudspeakers at head height 60 degrees apart at 1.3 metres from the subject.

Fourteen of the foundrymen made more errors of localisation with the earmuffs than without; the other man scored equally in both conditions. For the group as a whole, the total number of possible responses in one or other condition was 720; there were 76 percent correct responses with unoccluded ears and 50 percent correct responses when earmuffs were worn.

Atherley and Noble also reported an increase in confusions between left and right of the median plane when earmuffs were worn. The group as a whole made 13 contralateral responses with unoccluded ears; the number of contralateral responses rose to 113 when earmuffs were worn.

Atherley and Noble concluded that their findings, especially in regard to confusions between left and right, might be of importance from the point of view of safety of workpeople in industry.

Localisation is noticeably more difficult under reverberant conditions and many of the industrial environments where workers need to wear hearing protectors are far from anechoic. Therefore Atherley and Else (1971) extended the previous study to highly reverberant conditions to establish whether earmuffs

would also cause a decrease in localisation ability under the more difficult listening conditions. The Atherley and Else experiment was performed in a chamber with a seven-second reverberation time. The ten subjects in the study were undergraduates and as in the previous experiment, the 1kHz pure tone stimuli were presented from six loudspeakers placed at 60 degrees apart at head height surrounding the subject.

The 1kHz stimuli were far more difficult to localise under reverberant conditions than under anechoic conditions. For the group as a whole, the total number of possible responses in one or other condition was 480; correct responses amounted to 55 percent of the total when ears were unoccluded and 40 percent when ears were occluded with earmuffs. The wearing of earmuffs also increased the number of contralateral responses for the group under reverberant conditions from 16 without earmuffs to 42 when they were worn.

The two laboratory studies showed that earmuffs were capable of affecting the localisation of 1kHz pure tones under both anechoic and highly reverberant conditions, but the stimulus used in the experiments was not one that would be easy to localise.

Localisation of pure tones has been shown to be more difficult than the localisation of complex sounds by many authors: Ferree and Collins (1911); Stevens and Newman (1936); Jongkees

and van der Veer (1957); Nordlund (1962); Harris and Sergeant (1971). Clicks, for instance, are so much easier to localise than pure tones that the elimination of switching transients has always been a vital requirement in pure tone experiments and the ease with which wide-band noise can be localised has resulted in it being used as an auditary pointer in the localisation experiments of Sandel et al., (1955).

The real sounds heard in everyday life are complex sounds - sounds for which localisation is unlikely to depend uniquely on one of the four main localisation mechanisms: differences in interaural intensity, time and phase or pinnae function. Whereas localisation of the 1kHz pure tone stimuli used in the studies of Atherley and Noble and Atherley and Else could be expected to rely heavily on the cues of interaural phase differences. Stewart (1920) concluded, from his localisation experiments and calculations of phase differences at the ears for sounds of various frequencies, that localisation of pure tones between 100Hz and 1200Hz depends almost entirely on interaural phase differences. Support for the conclusion that interaural phase difference is the most important factor in direction perception at 1kHz can be found in the pure tone localisation studies of Stevens and Newman (1936); Sandel et al., (1955); Nordlund (1962) and others.

Higher frequency components in everyday sounds would also

provide cues from interaural intensity differences due to the diffraction of the sound by head and pinnae: Stevens and Newman (1936); Sandel et al., (1955); Batteau (1967).

The work of Feddersen et al., (1957) and Nordlund (1963) suggests that interaural intensity differences are unlikely to provide strong cues at 1kHz - the frequency used in the experiments with earmuffs.

The experiments of Gardner and Gardner (1973) on the effects of occluding parts of the pinna cavities and the experiments of Fisher and Freedman (1968) with pinna replicas have demonstrated the importance of the cues derived from multiple reflections at the pinna which were postulated by Batteau (1968). Pinna function could not be expected to provide cues at 1kHz, but it would provide cues for complex sounds.

Without doubt, earmuffs have been shown to affect localisation but the studies were restricted to stimuli which would not contain an abundance of cues. During the localisation of real complex sounds there might normally be an abundance of cues available from the four main localisation mechanisms; indeed, much of the information conveyed by the cues might well be redundant under many circumstances. It would be unwise to deduce from the evidence discussed so far that earmuffs would necessarily affect localisation of complex sounds. Even if occlusion of the ears by earmuffs does reduce the information

conveyed by a complex stimulus, localisation could be unaffected if sufficient information passed to allow accurate localisation.

Atherley and Noble found that stimulus sensation level was a material factor affecting the accuracy of localisation in the unoccluded condition, an observation that is in agreement with the findings of Butler and Naunton (1967). Atherley and Noble used sensation levels of 10dB, 20dB, 30dB and 40dB; accuracy of localisation improved with increasing sensation level. However, not surprisingly, the literature does not contain reports of localisation studies in which the very high sound levels likely to be encountered by the wearers of hearing protectors have been used as stimuli. It is not known whether localisation ability continues to increase with sensation level, or whether it limits or decreases at very high sensation levels. It is therefore impossible to predict whether the attenuation provided by earmuffs will itself aid or hinder localisation of high sound level sources.

So far it might appear that the localisation tasks used in the two studies with earmuffs would be far more difficult than the localisation of complex sounds encountered in industry, but at this point it must be remembered that the laboratory studies, as with almost all localisation experiments, were accomplished in environments practically devoid of background

noise. There is a dearth of information about the effect of masking noise on localisation - that which is available, from King and Laird (1930) suggests that background noise is likely to adversely affect localisation, as might be expected intuitively.

King and Laird used clicks as stimuli in their measurements of the minimum angular change in direction that could be correctly detected in 80 percent of the trials by subjects with unoccluded ears. The experiments were conducted in a sound-deadened room. The intensity level at which the clicks were delivered is not described in their paper, but when an 'audiometer buzzer' noise was introduced at 30dB below the level of the clicks, and from another direction, the minimum angular change of the clicks had to be doubled to obtain 80 percent correct responses. (The spectral composition of the noise from the 'audiometer buzzer' was not described by King and Laird in their paper.)

King and Laird showed that masking noise adversely affected localisation even at a high signal-to-noise ratio. There is no information available about the possible effects of masking noise on locasliation at the low signal-to-noise ratios often encountered in areas of factories where hearing protectors need to be worn, and it is impossible to predict whether the earmuffs would aid or hinder the localisation of sounds

presented at poor signal-to-noise ratios.

In many industrial situations, adequate protection could be provided by either earplugs or earmuffs. Under such circumstances the degree to which the hearing protectors affect localisation might be an important factor governing the choice between earplugs and earmuffs.

The two experiments of Atherley, Noble and Else did not attempt to investigate whether earplugs affect localisation. Earplugs do not cover the pinnae, nor do they provide such an obstacle for the diffraction of sound as do earmuffs. The effects of earplugs on localisation may be quite different from those of earmuffs. This could explain why I have not received complaints about loss of directional hearing from wearers of earplugs although I have received complaints from earmuff wearers from heavy engineering workshops, drop forges, foundries and chemical works.

Although earmuffs have been shown to affect localisation of 1kHz pure tones in both anechoic and highly reverberant conditions a number of questions must be answered before the practical significance of these findings in regard to hearing protector usage can be gauged:

1. Are earmuffs likely to have a detrimental effect on the localisation of complex sounds of high sound level - sounds which may convey an abundance

of localisation information, much of which may normally be redundant?

2. Is the localisation of complex sounds at the poor signal-to-noise ratios likely to be encountered at many industrial sites so unreliable that it may cease to be a precious and rewarding ability?
3. Might hearing protectors provide some benefit to the localisation of complex sounds in poor signal-to-noise ratios at high sound levels?
4. Are the effects of earplugs and earmuffs on the localisation of complex sounds of high sound level significantly different?

In an attempt to answer these questions two preliminary experiments were devised.

In the first experiment, localisation ability was tested in anechoic conditions with an easy-to-localise complex stimulus of high-intensity impact noise. Localisation ability was tested in each of three listening conditions: nothing in the ears; earplugs in the ears; and earmuffs covering the ears. The second experiment was a repeat of the first experiment in the presence of a high intensity masking noise.

Experiment I

Subjects: Ten subjects took part in the experiment; the

subjects were research staff and research students aged between 18 and 30 years. None of the subjects had worn hearing protectors habitually, although most had participated in hearing protector attenuation tests; the attenuation tests involved wearing hearing protectors for periods of between ten minutes and fifteen minutes on a few occasions. The hearing levels for both ears of each subject were within 15dB of audiometric zero (International Organisation for Standardisation, 1964) in the frequency range 500Hz to 6000Hz.

Stimuli: Bursts of recurrent impact noise of one second duration were used as stimuli. The impacts were delivered at a peak pressure level of 92dB (reference level: 20$\mu$Pa) and a repetition rate of one hundred impacts per second. The impacts (Figure 11) were derived from a 3.5kHz carrier wave modulated so as to produce an exponential decay of 1.5ms* in the envelope.

Apparatus: The subject was seated on a stool at the centre of an array of six loudspeakers in an anechoic room. The loudspeakers were at head height (1.25m) 60 degrees apart on the circumference of a circle of radius 1.5m, as shown in Figure 12. Another loudspeaker was positioned behind loudspeaker number 1 to provide random noise of 80dB(A) during the fitting of hearing protectors.

* The decay rate defined as the time taken for the sound pressure envelope to decay to $1/e$ (ie. 0.37) of its initial peak height.

The recurrent impact signal was produced by a waveform generator by a method described by Martin (1970). The recurrent impact signal was amplified and a selector switch directed the signal to exponential horn loudspeakers. The selector switch was ganged to a switched attenuator at the input to the amplifier. The switched attenuator was pre-set to equalise the output from each of the loudspeakers.

High attenuation earmuffs incorporating fluid seals (Amplivox Sonoguard) were used in the experiment. The glass down earplugs used in the experiment were folded by the subjects from loose material. They were instructed how to fit the hearing protectors and asked to adjust them in high intensity random noise. I checked the fit visually. The experiment was controlled from a room isolated from the anechoic chamber; a communication system allowed subject and experimenter to converse at any time.

Procedure: For each subject the stimulus was presented twelve times in each listening condition (ie. unoccluded ears; ears occluded by earplugs; ears occluded by earmuffs). The order of presentation from the six loudspeakers was randomised; the impact stimulus could come from the same loudspeaker on two consecutive occasions. The order in which the listening conditions were tested was randomised for the ten subjects. A brief rest period was given between listening conditions,

during which the subject was instructed how to fit the hearing protectors if the next test condition was with occluded ears. The subject was provided with a chart, similar to Figure 12, positioned directly below the loudspeaker in front of him. The subject was requested to keep his head facing towards the chart. The subject reported verbally the number of the loudspeaker position from which he thought the impact noise originated. The subjects were instructed to respond to every stimulus even when they were unsure about the direction. Two practice trials were given in each listening condition; the loudspeakers used for the practice trials were chosen at random.

Results: Correct Responses

The totals of correct responses made by each subject in each of the listening conditions are shown in Table 5. For the group as a whole, the total number of responses in each listening condition was 120; the proportion of correct responses made in the unoccluded condition was 81 percent. When earplugs were worn, 83 percent of the responses were correct, but when earmuffs were worn, the proportion of correct responses was reduced to 53 percent. A Friedman's non-parametric two-way analysis of variance (Siegel, 1956) showed the overall effect of listening condition to be significant.

(Number of correct responses: ten subjects x three

listening conditions; Friedman's $X_r^2 = 10.9$, df = 2, $p \leq 0.005$.)

The difference between the numbers of correct responses for the unoccluded condition and earplug condition was not significant; when earmuffs were worn, significantly fewer correct responses were made than in either unoccluded or earplug conditions. Eight of the ten subjects made fewer correct responses when they wore earmuffs than when they used unoccluded ears.

(Number of correct responses: ten subjects x two listening conditions; Wilcoxon matched pairs signed ranks test (Siegel, 1956); N = 8 or 9, T = 0, $p < 0.005$ for a one-tailed test.)

Errors

There were no contralateral responses in any of the listening conditions; the subjects always placed their responses to the correct side of the median plane.

The total number of errors made in each listening condition by the group as a whole are given in Table 6; the errors are sub-divided into: responses in error by one loudspeaker position; responses in error by more than one loudspeaker position; responses to the rear of the stimulus position; and responses to the fore of the stimulus position. The error types are also shown as percentages of the total errors made in each listening

condition. The variation in one-place errors with listening condition was shown to be significant.

(Number of one-place errors; ten subjects x three listening conditions; Friedman's $X_r^2 = 11$, df = 2, $p < 0.005$.)

The variation in the number of errors of greater than one place was not significant.

Analysis of the one-place errors showed that significantly more one-place errors were made when earmuffs were worn than when either earplugs were worn, or nothing was put in the ears.

(Number of one-place errors; ten subjects x two listening conditions; Wilcoxon, N = 8 or 9, T = 0 $p \leqslant 0.005$ for a one-tailed test.)

The earplugs did not cause significantly more one-place errors than occurred with unoccluded ears.

Experiment 2

The second experiment took place two weeks after the first experiment. The same subjects and experimental procedures were used as in the first experiment, but the loudspeaker used to generate white noise for the fitting of the hearing protectors was switched on for the duration of the experiment. The white noise was at a level of 86 dBSPL at the ears of the subjects.

Results: Correct Responses

The totals of correct responses for each subject in each listening condition are shown in Table 7. Six of the ten subjects scored fewer correct responses when they wore earmuffs then when they used unoccluded ears. Six of the subjects scored more correct responses when they wore earplugs than when they had unoccluded ears. Only one subject had fewer correct responses when wearing earplugs than when using unoccluded ears. Nine of the ten subjects scored fewer correct responses in the earmuffs than they did wearing earplugs. For the group as a whole 65 percent of the responses were correct when nothing was worn in the ears. When earplugs were worn 71 percent of the responses were correct. However, when earmuffs were worn the proportion of correct responses was reduced to 53 percent. The effect of listening condition was shown to be significant overall.

(Number of correct responses: ten subjects x three listening conditions; Friedman's $\chi^2_r = 7.8$, df = 2, $p < 0.025$.)

The difference between the numbers of correct responses in unoccluded and earplug conditions was not significant.

(Number of correct responses: ten subjects x two listening conditions (unoccluded ears and earplugs): Wilcoxon N = 8, T = 9, $p \gg 0.05$ for a two-tailed test.)

When earmuffs were worn significantly fewer correct responses were made than in either unoccluded or earplug conditions.

(Number of correct responses: ten subjects x two listening conditions (earmuffs and earplugs): Wilcoxon N = 10, T = 3.5, $p < 0.005$ for a one-tailed test.)

(Number of correct responses: ten subjects x two listening conditions (unoccluded ears and earmuffs): Wilcoxon N = 7, T = 3.5, $p < 0.05$ for a one-tailed test.)

Errors

There were no contralateral responses in any of the listening conditions; the subjects always placed their responses to the correct side of the median plane.

The total numbers of errors made by the group as a whole are given in Table 8, in which they are sub-divided by magnitude and direction. The error types are also listed as percentages of the total errors made in each listening condition.

Analysis of the errors failed to show a significant increase in the numbers of any one type of error.

Results of Comparisons Between Experiments 1 and 2

When the experiment was repeated in the presence of high

intensity white noise there was a significant reduction in the numbers of correct responses for the unoccluded condition - 81 percent correct was reduced to 65 percent correct by the presence of the background noise.

(Number of correct responses: ten subjects x two experiments; Wilcoxon N = 9, T = 3, p = 0.01 for a one-tailed test.)

The numbers of correct responses made whilst wearing earplugs was also reduced when masking noise was present - 83 percent correct was reduced to 71 percent by the presence of the background noise.

(Number of correct responses: ten subjects x two experiments; Wilcoxon N = 9, T = 7, $p < 0.05$ for a one-tailed test.)

The masking noise did not significantly reduce the number of correct responses when earmuffs were worn - 53 percent correct in both experiments.

Discussion

The stimuli used in the experiments were one-second bursts of recurrent impact noise delivered at a peak pressure level of 92dB (reference 20$\mu$Pa). The impacts were derived from a 3.5kHz carrier wave with the envelope modulated to an exponential decay with a repetition rate of one hundred impacts per second.

This type of complex stimulus should have provided the subjects with an abundance of localisation cues; interaural phase and time differences from the low frequency produced by the repetition rate and interaural intensity differences and cues from pinnae function from the high frequency components associated with the individual impacts. An easier localisation task would probably be difficult to devise without perhaps allowing head movements or using complex stimuli with which all subjects were very familiar.

Many authors have demonstrated that extra cues for localisation can be gained by movement of the head, eg. Young (1931); Wallach (1940); Thurlow and Runge (1967); Thurlow, Mangels and Runge (1967). However, Pollack and Rose (1967) have questioned the value of head movements except for sustained sounds which permit gross reorientation of the ears to the source and it is by no means certain that use could be made of head movement when determining the direction of a very brief danger signal in an industrial setting.

Batteau (1968) has suggested that pinna function might provide more cues if the stimulus was a very familiar sound. However, the most important sounds to localise correctly in industry may be those which result from the unplanned and unusual events.

The first experiment therefore showed that earmuffs can have a detrimental effect on the localisation of a relatively easy-to-localise complex stimulus. The wearing of earmuffs reduced the proportion of occasions on which the stimulus could be localised within 30 degrees of its true position from 81 percent with unoccluded ears to 53 percent with the earmuffs worn.

If the complex stimulus did indeed carry an abundance of localisation cues it would appear that the loss of information caused by wearing earmuffs was not fully compensated by the wearer making greater use of the remaining cues. One tenuous explanation for this might be that the earmuffs transform the information in some way, causing confusion rather than simply removing the cue.

The introduction of high intensity white noise (80dB SPL) as a background noise in the second experiment made the localisation task significantly more difficult for the unoccluded ears. The percentage of correct responses in the unoccluded condition was reduced from 81 percent to 65 percent by the introduction of the background noise.

The subjects were less drastically affected by the introduction of the background noise however, than they had previously been by the wearing of earmuffs.

(Decrease in the number of correct responses: ten

subjects x two reductions in localisation performance (wearing earmuffs without background noise and using unoccluded ears following the introduction of background noise); Wilcoxon N = 9, T = 6, $p < 0.05$ for a two-tailed test.)

Although performance under both unoccluded and earplug conditions was reduced by the introduction of the background noise the performance wearing earmuffs remained unchanged with 53 percent correct responses. At first sight it might appear that the wearing of earmuffs reduces localisation to a minimum which cannot further be affected, but it must be remembered that even when earmuffs were worn, three times as many correct responses were made as would have been expected if the subjects had no localisation ability*. It is almost as though the cues affected by earmuffs are those which would similarly be masked by the background noise.

The earmuffs certainly did not appear to provide the listeners with any positive benefit when localising in high ambient noise levels - though the levels used in the experiment were lower than those likely to be encountered by most wearers of earmuffs in industry. At this point it is interesting to note that earplugs were not shown to have a detrimental effect on localisation of the high intensity complex stimulus under

* Approximately 17 percent of the responses would have been correct if the subjects had responded at random among the six loudspeaker positions.

either quiet or high background noise conditions. Earplugs as well as not covering the pinnae would also have provided less attenuation of the stimuli - although Atherley and Noble have already shown that attenuation is unlikely to account for the detrimental effect caused by earmuffs in their experiment.

Noble and Russell (1972) reporting on the results of a study of the effects of earplugs and earmuffs on localisation, also found that localisation was significantly worse with earmuffs than when earplugs were worn. However, Noble and Russell did observe some impairment of localisation while earplugs were worn as compared with the unoccluded condition.

Noble and Russell devised their experiments in an attempt to establish why localisation is impaired by earmuffs rather than to examine the likelihood of such impairment existing under industrial conditions. They used an experimental rig similar to those used by Atherley and Noble, and Atherley and Else, but as well as using the 1kHz pure tone stimulus they also used white noise as a stimulus: it could be presented from any one of the six loudspeakers which surrounded the seated subject at head height 60 degrees apart.

Noble and Russell employed fifteen first-year psychology students as subjects. The stimuli were presented to them at a sensation level of 20 decibels.

In Table 9 the results of the experiments with impact

noise are compared with other localisation experiments in which both ears have been occluded.

Comparison of the results of Experiment I with the results of the study by Noble and Russell with low intensity white noise stimuli, suggests that white noise is easier to localise than impact noise. Although this may be true there are at least two reasons to expect more errors with Experiment I.

The method used by Noble and Russell allowed non-response but Experiment I used a forced-choice response method. Therefore the uncertain responses did not enter the analysis for the experiment of Noble and Russell.

The positions of the loudspeakers used by Noble and Russell were the same as in the previous work of Atherley and Noble (1970) and Atherley and Else (1971); loudspeakers were not placed directly in front of, or directly behind, the subjects. These positions in the median plane are recognised to be difficult for localisation; the experiments with impact noise included these positions and could be expected to result in more errors.

The results from the experiments of Noble and Russell shown in Table 9 clearly demonstrate the accuracy of localisation when the complex stimulus was used as compared with the 1kHz pure tone of the same sensation level. The complex stimulus was accurately placed more than twice as many times

as the pure tone for the equivalent unoccluded conditions.

Atherley and Noble reported an increase in the number of confusions between left and right when earmuffs were worn. In the unoccluded condition 7.5 percent of the errors that were made involved confusion between left and right; the proportion increased to 31.4 percent when earmuffs were worn. Atherley and Else in their experiment in reverberant conditions found that 7.3 percent of the errors in the unoccluded condition involved confusion between left and right; the proportion increased to 14.5 percent when earmuffs were worn. In the experiment of Noble and Russell with pure tones the corresponding proportions were 12.4 percent for the unoccluded condition and 25.2 percent when earmuffs were worn; earplugs did not increase the proportion of lateral confusions. When Noble and Russell used white noise stimuli they had no lateral confusions in the unoccluded condition; when earplugs were worn 1.3 percent of the errors were confusions between left and right; when earmuffs were worn the proportion increased to 8 percent. Noble and Russell found that although earplugs significantly increased front/rear confusions, these did not increase confusions between left and right. Earmuffs were found to increase the more serious confusions between left and right.

In both of the experiments using impact noise as stimuli

there were no confusions between left and right. However, an error of at least 120 degrees would be needed before it would be registered as a confusion between left and right. In the loudspeaker orientations used in the other experiments an error of only 60 degrees could be registered as a lateral confusion.

It should be recorded at this point that after controlling both experiments the experimenter was left with the impression that the trials in which the earmuffs were worn took longer. There is evidence in the literature to show that in localisation experiments correct responses have significantly shorter response times than incorrect responses (Holding and Dennis, 1957).

## Conclusions

The results from the experiments with impact noise stimuli have added weight to the argument that earmuffs are likely to adversely affect the localisation ability of the wearer.

In the first experiment localisation of a high intensity complex stimulus (recurrent impact noise) in quiet semi-anechoic laboratory conditions was shown to be adversely affected by earmuffs, whereas earplugs were not shown to affect localisation. The conclusion that earmuffs affect localisation more than earplugs is in agreement with the findings of Noble and Russell. However, in their experiments

with low intensity white noise stimuli earplugs reduced localisation ability although not so much as earmuffs - for example, confusions between left and right were not significantly increased by earplugs although they were by earmuffs.

The introduction of high intensity white noise as a background noise during the second experiment made the task of localising the impact noise stimuli more difficult both when the ears were unoccluded and when earplugs were worn. Earmuffs were shown to adversely affect localisation in the high background noise level, whereas earplugs were not shown to have an effect. More than half of the subjects scored more correct responses when they wore earplugs than when they had unoccluded ears, although no statistically significant benefit, attributable to earplugs, was established.

The introduction of background noise impaired localisation ability of the subjects when they had unoccluded ears. However, when earmuffs were worn by the subjects their localisation performance was apparently not further reduced by introducing background noise.

In the laboratory studies discussed so far, earmuffs have been shown to adversely affect localisation and the effects produced by earmuffs have been shown to be greater than those produced by earplugs. However, the laboratory conditions under which the localisation has been tested have differed from the

conditions under which localisation might be used by hearing protector users in industry.

The evidence appears to be accumulating to support the view that earmuffs affect localisation more than earplugs. It will be necessary, however, to study the relative effects of earplugs and earmuffs more closely under more realistic conditions, with subjects from the populations required to wear hearing protectors, to establish the practical significance of the findings.

# CHAPTER FOUR

## THE EFFECTS OF HEARING PROTECTORS ON LOCALISATION ABILITY - STUDIES AT A FOUNDRY

As previously stated, earmuffs have been shown to affect localisation ability under laboratory conditions by Atherley and Noble (1970), Atherley and Else (1971), Noble and Russell (1972) and in the studies described in the previous chapter. Although all the studies have demonstrated the effect, we do not know by what means the earmuffs reduce localisation ability.

However, even if we did know which of the localisation mechanisms were affected in the laboratory studies we would be unable to predict by how much localisation of real sounds in an industrial setting would be affected. A century of localisation studies since Lord Rayleigh's early experiments (1876)* has improved our knowledge of the mechanisms which contribute to localisation - differences of interaural phase, time and intensity; pinnae function; and head movements but we are unable to predict the manner in which the mechanisms will combine to provide localisation for a real sound under realistic industrial listening conditions. We are far from being able to predict the ease or difficulty with which a warning shout will be localised against a high level of background noise.

* quoted by Thompson (1879)

Earmuffs must be shown to have a deleterious effect on localisation under conditions similar to those under which hearing protectors would usually be worn before the potential for increasing danger can be said to have been established.

It is admissable to study the effects under unrealistic conditions whilst attempting to explore generative mechanisms but it would be inadvisable to call for a change in the methods of selecting hearing protectors from the results of those studies which have used very low sound level stimuli, often pure tones, under quiet conditions. The previous studies have usually forced the subjects to rely on fewer cues than would normally be available to them.

This chapter describes studies of localisation under conditions that were more like those encountered by hearing protector users. The studies explore the utility of localisation with unoccluded ears under such conditions; examine whether hearing protectors are likely to significantly affect localisation; and in particular whether earplugs are likely to affect localisation less than earmuffs.

The co-operation of a large steel foundry made it possible to extend previous localisation studies to more realistic conditions. The foundry was an especially appropriate setting because the complaints from foundrymen at another

foundry some years before had started the research into the effects of earmuffs on localisation (Atherley and Noble, 1971).

Two groups of employees agreed to participate in the experiments; twenty-one foundrymen who were employed in noisy occupations and most of whom had impaired hearing; and twenty-one office employees from much quieter environments (unfortunately, three of the office employees, who agreed, were unable to participate in the experiments for various reasons).

Recorded warning shouts were chosen as stimuli for the experiments because these were the warning sounds about which foundrymen had often expressed concern. The shouts were presented against a background of "pink" noise. The spectrum from "pink" noise is similar to the flat spectrum often encountered when measuring background noise in foundries, but the "pink" noise provides a more consistent level and does not contain individual distracting sounds.

The subjects in the foundry experiments were free to choose any direction (from 360 degrees of arc) in the horizontal plane for their responses - they were not confined to selecting one of six directions (60 degrees apart) as had been the case in all previous experiments. It was hoped that the response system would allow detection of smaller errors

and enable the effects of earplugs and earmuffs to be more easily quantified. The time taken to respond was automatically recorded for each response.

The experiments at the foundry were planned to explore the following questions:

1. Are hearing protectors likely to adversely affect the localisation of warning shouts in high background noise levels?
2. Are earmuffs likely to produce greater reductions in localisation ability than would be caused by earplugs?

In this chapter these two questions will be explored for two types of industrial users of hearing protectors: those who have not been habitually exposed to noise at work and have not previously worn hearing protectors; and those who have been habitually exposed to high levels of noise and have had some experience of wearing hearing protectors.

## Experiments

The foundry was surveyed to find a suitable site for the experiments. All potential sites located within the foundry perimeter presented one or more of the following problems: physical safety for subjects under tests; high ambient noise level; security for experimental equipment. It was therefore

agreed that the sports pavillion on the adjoining sports field would be made available for the experiments. The largest room in the pavillion had a floor area of only approximately thirty square metres and was highly reverberant. A less reverberant (3.6m x 3.6m x 2.4m) chamber was therefore constructed within the room. Walls and ceiling were clad with 25mm absorbent polyurethane foam with an air space of approximately 100mm between the foam and the plywood walls and ceiling of the chamber. The floor of the chamber was covered with absorbent polyurethane foam to a depth of 50mm.

Subjects

Fettlers:

Twenty-one men who worked in noisy areas in which castings were cleaned and finished agreed to take part in the experiments. All were subjected habitually to noise exposures considerably in excess of the equivalent of 90dB(A) for eight hours per day. Table 10 provides a summary of their occupations and associated equivalent-continuous sound levels. All of the fettlers had some experience of wearing glass down earplugs or earmuffs, but when asked, only six of them said they usually wore glass down earplugs and only four said they usually wore earmuffs. Those who said they usually wore earplugs or earmuffs are indicated in Table 11.

Office Employees:

Eighteen male office employees participated in the experiments. They were all employed in general offices distant from the noisy foundry areas. In the normal course of their employment, they would not have been required to enter the high noise-level areas.

Ages:

Fettlers between the ages of seventeen years and sixty-four years took part in the experiments. The age of office employees ranged between nineteen and sixty years. The distributions of ages within the two subject groups is outlined in Table II . The two groups had similar age distributions.

Hearing Levels:

The foundry's medical department did not have audiometric facilities and therefore an automatic audiometer and an audiometric booth had to be installed temporarily in the works' medical centre.

Atherley's (1964) measurements of the recovery from temporary threshold shift in weavers have highlighted the difficulty of determining "resting thresholds". No attempt was made to measure the "resting thresholds" of the subjects used in these experiments because of the difficulty of determining "resting thresholds"; and because the main

experiments would be attempted by the subjects during their working shifts.

It was not possible to measure the hearing of the subjects at the same temporal position in their workshift as were used for the main experiments. However, all audiometry and all main experiments took place at least two hours after the start of the fettlers' shift. Office employees were allowed to take part in audiometry and main experiments at any time during their working day. The results of the pure tone audiometry are described in Appendix VI. The distributions of mean hearing levels for both ears from the frequencies 0.5, 1, 2, 3, 4, and 6kHz, for fettlers and office employees, are displayed in Figure 13.

The median hearing levels for the fettlers and office employees were $30\text{dBHL}_{\overline{0.512346}}$ and $10\text{dBHL}_{\overline{0.512346}}$ respectively.

Stimuli

A shouted warning from the works' safety officer was recorded with a high quality tape recorder in the semi-anechoic chamber. The safety officer chose to use the words 'watch out'.

The pressure-time characteristics of the shouted warning are illustrated in Figure 14 . This has been taken from a recording made at the position occupied by the subject's head during the main experiments. The shout was presented at a

peak pressure level of 106dB (reference level: 20 μPa). Tape-loop copies of the shouted warnings were made and these were presented through the amplifier and loudspeaker as shown in Figure 15.

The shout was presented against a background of 'pink' noise* which was generated from a loudspeaker positioned approximately one metre above the head of the seated subject. The 'pink' noise could be presented at either 75dB(A) or 95dB(A) at the position occupied by the subject's head.

Note:

Many subjects reported that the shouts sounded very realistic, but a few of the fettlers thought that the background noise was 'coming at them' rather than 'going away from them, as it did in their jobs'.

During the experiment the shout was presented from the nine positions shown in Figure 16. Thus the stimulus was presented at 22.5 degree intervals between directly infront of the subject and directly behind the subject.

Apparatus

The subject was seated at a table at the centre of the semi-anechoic chamber. The loudspeaker which was used to produce the background noise was directly above the subject's

* noise having equal average energy in each octave band

head. The subject was surrounded by a circular black curtain at a radius of 1.2m as shown in Figure 17 . The loudspeaker through which the shout was presented was mounted on a counterbalanced boom; it was at the height of the subject's head outside the black curtain and could be moved to any angular position around the seated subject. The black curtain eliminated all visual cues to the position of loudspeaker and boom for the subject seated within.

A pad of response diagrams (Figure 18 ) was clipped to a small table (surface area approximately $0.2m^2$) at which the subject was seated. During the experiments the semi-anechoic chamber was in darkness except for a small pool of light directed onto the response diagram from above. A white reflective ribbon (40mm wide) was pinned to the black curtain directly infront of the subject to act as a reference.

A transient signal recorded in parallel on the second track of the stimulus tape-loop was used to start a digital timer at the same time as the shout was presented to the subject. A microswitch in the pen, which the subject used to mark the position from which he thought the shout had originated, was used to stop the digital timer when the subject marked the circle on the response diagram.

The wire to the pen was concealed inside the cord which was used to secure the pen to the table. Subjects were not

told that the response times were being recorded because this might have caused them to sacrifice accuracy for speed. They were asked to mark the position from which they thought the shout had come as soon as they had decided. Subjects were used to seeing pens secured to table tops in the fettling shop and offices.

Procedure

Each subject was asked to determine the direction from which the shout originated for each of the nine loudspeaker positions in both background noise levels for each of the three listening conditions: nothing in ears; earplugs in the ears; and earmuffs over the ears.

Each subject also attempted to mark the position of a light source placed at each of the nine loudspeaker positions. The details of these visual control experiments are detailed in Appendix VII. The visual experiments were included so that errors and bias brought about by the use of the response procedure could be considered during the interpretation of the auditory localisation results.

The procedure followed with each subject is shown in the flowchart in Figure 19 . The procedure was explained to the subject before he was taken into the semi-anechoic chamber and he was given an opportunity to ask questions about the

procedure. The subject was then seated at the table and the lights dimmed. The light source was moved to one of the positions $V_1$, $V_2$ or $V_3$ in Figure 20 and the subject was asked to mark its position on the first response diagram and then to turn over to the next response diagram in the pad before him. The subject repeated this procedure for the other two visual practice positions during which time the experimenter observed the subject from outside the curtained area, to ensure that the subject marked the circle on the response diagram and used a fresh response diagram for each response.

The subject was then given five practice trials with the warning shout. The five positions chosen from among the nine loudspeaker positions were selected from random number tables. Three of the practice trials were conducted in the background noise level of 75dB(A) and two in 95dB(A). The results from the practice trials were recorded but not analysed.

The experimenter returned to the subject after the initial eight practice trials to assure him that he was complying with the initial instructions and to ensure that he knew what to expect during the remainder of the experiments.

The trials for the experiments were divided into three listening condition blocks (nothing in the ears; earplugs in the ears; earmuffs over the ears). A Latin-squares design was used to select the order of blocks for each subject to

ensure that within both office employee and fettler groups earplugs were used for the first block as often as earmuffs and nothing in the ears, and similarly for the second and third blocks. The order of listening conditions used by each subject is shown in Table 12.

Within each listening condition the order of nine presentation positions was randomised separately for every trial. The level of background noise was alternately 75dB(A) and 95dB(A) throughout all listening conditions.

The eighteen trials in each listening condition block were preceded by a presentation in 75dB(A) from position P1 or P2 and another in 95dB(A) from P2 or P1. The results from the two practice trials in each listening condition were discarded.

The visual control trials for each of the nine loudspeaker positions took place after the completion of the auditory localisation tests on the same occasion as the localisation tests.

The time taken by the subjects to complete the initial practice trials and subsequent listening condition blocks and visual control experiment was approximately forty minutes. The subject was also given a ten-minute break between the second and third test blocks during which coffee was provided. Discussion of the experiment was avoided during the break.

The total time taken between the subject's arriving and leaving the vicinity of the test was approximately one hour. The subjects were therefore away from their work stations for approximately eighty minutes.

During the experiments I controlled the position of the visual and auditory stimuli from one corner of the semi-anechoic chamber outside the black curtain. The fitting of the earplugs or earmuffs was not supervised. The earplugs were pre-formed glass down material; the earmuffs were a high attenuation type*.

The subjects were not told during or after the experiments about their performance under the three different listening conditions.

* The earmuffs used during the experiment were type EMU42 manufactured by Protector Safety Products Ltd.

Analysis of Results from Foundry Experiments

The experiment was planned as a four-factor experiment with repeated measures of three of the factors** A split-plot factorial design was chosen to facilitate the use of powerful parametric analysis of variance statistical techniques for the exploration of main effects and first order interactions.

** The experiment employed: two types of subject; two levels of signal to noise ratio; three levels of listening condition; and nine stimulus positions. Repeated measures were taken of all factors other than type of subject, therefore under the classification system described by Kirk (1968) the design could be classified as $SPF_{2.239}$.

However, during the course of the experiments and subsequently from the analysis of the visual control experiment and the conduct of the experiments, a series of factors came together to militate against the use of the parametric analyses.

The analysis of the visual control experiment (summarised in Appendix VII ) clearly indicated that the error variance associated with the combination of visual task and response system varied markedly with stimulus position. The error variance in the localisation studies also showed marked heterogeneity. The responses of the office employees to the warning shouts in the 75dB(A) background noise level clearly demonstrate the heterogeneity. The variance for response to shouts from position 0 (directly ahead) was 5679 degrees$^2$; for position 1 the variance was 481 degrees$^2$ and for position 2 (directly to the subject's right) the variance was 126 degrees$^2$.

(Hartley's Fmax test for homogeneity of error variance: office employee subject group; error variance x nine stimulus positions; Fmax $\geqslant$ 45 with df = 9 and 17, $p \ll 0.01$.)

Although homogeneity of error variance is a recognised prerequisite for the use of the analysis of variance, the presence of heterogeneous error variance does not preclude the use of the parametric analysis.

Tukey (1949)*has shown that analysis of variance can be applied, provided that a suitable transformation can be found to normalise the error variance.

Therefore heterogeneity of error variances did not in itself present an insurmountable barrier to the use of analysis of variance; indeed, Hays (1970) says that the modern opinion is that analysis of variance should be carried out without a preliminary test where the number of cases in the various samples are equal, at least so long as the interest is in the differences in means rather than in the different degrees of variability caused by different treatments. But of course one of the original reasons for choosing analysis of variance was the facility it provides for studying degrees of variability and as fate would have it, the subject groups were of unequal size in the final outcome.

Of course, the inequality of the size of the subject groups would in itself not preclude the use of analysis of variance. Kirk (1968) has indicated that in a situation such as this in which one subject group is smaller than another for reasons unrelated to the conduct of the experiment an "unweighted means solution" can be used to compensate for the inequality. But of course, the "unweighted means solution" would only have been valid if the error variances had been normalised.

* quoted by Kirk (1968)

Another factor which militated against the use of the analysis of variance arose because some warning shouts were completely missed by the subjects, especially the fettler subjects when they wore earmuffs and listened in the higher background noise level. Although the levels of warning shout and background noise level had been set following preliminary trials, with both normally hearing subjects and subjects who had been exposed to noise for many years, during the course of the experiment 56 warning shouts were missed completely out of a total of 1404 presentations (approximately 4 percent). The missing values could be expected to have a perturbing effect on the analysis because of their concentration within one block - the block in which fettlers were tested wearing earmuffs. Fifty-five percent of the missing values (31 of the 56 missed shouts) occurred when fettlers were wearing earmuffs, which amounted to 16 percent of the stimulus presentations within that block.

Techniques are available for estimating missing values, for the purposes of the analysis of variance, which have apparently been lost for reasons not unrelated to the conduct of the experiment: eg. Yates (1933) and Anderson (1946). But the complexities associated with their use in experimental designs having three or more treatments are considerable.

In view of these confounding factors, I chose to forfeit the higher power and facility for exploring interactions apparently available with the parametric analysis of variance in favour of the robustness and ease of application under such difficult circumstances provided by non-parametric tests. Hence, non-parametric tests have been used almost exclusively for the analyses of the results presented in this chapter.

The use of non-parametric tests for the analysis of results from complicated experimental designs can lead the experimenter unwittingly to adopt a high error rate* whilst seeming to test to a stringent significance level for individual comparisons.

If multiple pair comparisons are made at a significance level of $\alpha$, the probability that at least one of the overall conclusions is wrong is considerably greater than $\alpha$.

Therefore wherever possible, during the analyses, overall effects have been tested before making multiple pair comparisons**.

* Probability that any one of a number of hypotheses will be falsely declared significant.

** This procedure should have ensured some guard against the over-interpretation of individual significance tests. It is unlikely that an individual effect would have been located without there having been some real effect present. However, Hays (1970) has shown that if more than one individual comparison from a set of comparisons showed significant effect at a significance level of $\alpha$, an error rate of K x $\alpha$ would have been accepted that each of the results had occurred by chance. Where K different significance tests have been applied to the data at a significance level of $\alpha$.

The analyses of results from the foundry experiments which follow have been sub-divided into five sections.

1. Perception of Warning Shouts: an analysis of the unexpected and potentially vitally important apparent reduction in the perception of warning shouts when earmuffs were worn by the noise-exposed fettlers.

2. Localisation of Warning Shouts - Response Time: an analysis of effects of hearing protectors on the time taken to accomplish a localisation task.

3. Localisation of Warning Shouts - Total Angular Error: an analysis of total angular response error for the purposes of studying the magnitude of the effects produced by earplugs and earmuffs.

4. Localisation of Warning Shouts - Contralateral Responses: an analysis of errors in determing from which side of the subject (left or right) the shout had originated, to determine whether either earplugs or earmuffs, or both, produce these potentially serious errors.

5. Localisation of Warning Shouts - Errors Greater than 30 Degrees: an analysis of errors of greater than 30 degrees magnitude for the purposes of comparison with previous studies.

## RESULTS

### 1. Perception of Warning Shouts

None of the office employees missed any warning shouts when these were presented against a background noise of 75dB(A). Only one of the fettlers missed a warning shout presented against the 75dB(A) background noise level - the missed shout was from directly behind the subject whilst he was wearing earmuffs.

In the higher 95dB(A) background noise level seven of the office employees missed warning shouts and thirteen of the fettlers missed warning shouts. One of the fettlers was unable to hear any warning shouts when he wore earmuffs in the higher noise level. In Table 13 the numbers of warning shouts missed by each subject group under the three listening conditions (nothing in the ears; earplugs in the ears; earmuffs over the ears) are shown separately for the 75dB(A) and 95dB(A) background noise levels. As can be seen from Table 13 , in the higher noise level the fettlers missed five warning shouts when they had nothing in their ears and nine when they wore earplugs; the number of warning shouts missed increased to thirty-one when earmuffs were worn.

A Friedman's non-parametric two-way analysis of variance (Siegel, 1956) does not show conclusively that listening condition significantly affects the perception of warning

shouts in the high background noise level.

(Number of missed shouts: twenty-one subjects x three listening conditions; Friedman's $Xr^2 = 2.8$, df = 2, $0.3 > p > 0.2$.)

It would be unwise to assume from the Friedman's analysis that the fettlers' perception of warning shouts would not be reduced by the wearing of earmuffs.

Therefore the correlation between the number of shouts missed by a subject when he wore earmuffs and his hearing level was investigated (Figure 21 ). A significant correlation was discovered:

(Correlation between average hearing level for both ears $dBHL_{\overline{0.512346}}$ and number of warning shouts missed when earmuffs worn x 39 subjects: Spearman's rank correlation coefficient rs = 0.32, p = 0.05 for a two-tailed test.)

I noticed during the experiments that most of the shouts which were missed originated directly behind the subjects. The distribution of missed shouts amongst the loudspeaker positions is illustrated in Figure 22.

When hearing protectors were not worn, the few warning shouts that were missed (a total of eight shouts) came from directly behind the subjects (six shouts) or directly infront of the subjects (two shouts).

Similarly, when earmuffs were worn more shouts were missed from directly behind than from any other speaker position, but the wearing of the earmuffs also caused shouts to be missed from all the other loudspeaker positions. Thirty-six shouts were missed when earmuffs were worn. Only ten of these came from directly behind the subjects.

2. Localisation of Warning Shouts - Response Time

The average times taken to respond to the warning shout are shown separately for office employee and fettler subject groups in Table 14 for each combination of listening condition and background noise level. The response times are sub-divided by stimulus position.

The mean response times per stimulus under all listening conditions were greater for the high background noise level. Analysis of the average response time per stimulus position showed that the office employees took longer to respond when listening in the higher background noise level.

(Number of times average response time for the office employees was longer in the high background noise level: nine stimulus positions x three listening conditions; $X^2 = 7.2$ with df = 2, $0.05 > p > 0.02$.)

The equivalent analysis for the fettlers did not show with such certainty that the higher background noise level

caused slower responses - however it must be remembered that the averages represented in Table 14 for fettlers wearing earmuffs was taken for the higher noise level from a sample from which 16 percent of the responses had been missed altogether.

(Number of times average response time for fettlers was longer in the high background noise level: nine stimulus positions x three listening conditions; $X^2 = 4.6$ with df = 2, p = 0.10 )

The variation in response time with stimulus position is illustrated in Figure 23 for the warning shouts detected against the lower background noise level of 75dB(A). For both subject groups combined in each listening condition stimulus position significantly affected the average time take to respond.

(Friedman's non-parametric two-way analysis of variance - average response time in lower background noise level: nine stimulus positions x six groups (ie. two subject groups x three listening conditions); Friedman's $Xr^2 = 35.9$, with df = 8, $p < 0.001$ )

For all listening conditions the time taken to localise shouts appears to increase with proximity to the median plane.

A similar distribution of response time with stimulus

direction is seen in Figure 24, where the average times taken to localise warning shouts in the higher background noise level, 95dB(A), are shown for the subject groups combined in each listening condition.

Twenty subjects missed one or more shouts during the experiments because they were inaudible to them. The majority of these were missed whilst the subjects were wearing earmuffs. Therefore for the purposes of studying the effects of hearing protectors on response time a reduced sample has been extracted from the two subject groups. Six fettlers and seven office employees responded to all warning shouts and had their response times recorded*.

The total time taken by each of these subjects to respond to warning shouts from all nine stimulus directions is shown in Table 15 . The response times are sub-divided by listening condition and background noise level.

Most of the subjects with severe hearing losses were excluded from the reduced sample by this data extraction procedure - differences between subject groups have therefore not been studied further.

Friedman's non-parametric analyses of variance showed that hearing protectors significantly affect the time taken

* One or more individual response times went unrecorded during the tests with six of the subjects, although they did respond to all warning shouts and had all their response directions recorded. This was due to equipment and operator errors.

to determine the direction of warning shouts in both low and high background noise levels.

(Low background noise level (75dB(A)) - total response time for the nine stimulus directions: thirteen subjects x three listening conditions; Friedman's $X_r^2 = 5.7$, df = 2, $p \simeq 0.05$ )

(High background noise level (95dB(A)) - total response time for the nine stimulus directions: thirteen subjects x three listening conditions; Friedman's $X_r^2 = 4.8$, df = 2, $0.10 > p > 0.05$ )

Further analysis showed that the increase in time taken to respond when earmuffs were worn was statistically significant in both low and high background noise levels. Differences between other listening conditions were not statistically significant ($p \gg 0.10$).

(Low background noise level (75dB(A)) - total response time for nine stimulus directions: thirteen subjects x two listening conditions (nothing in ears, and earmuffs over ears); Wilcoxon matched-pairs signed-ranks test; N = 13, T = 19, $p < 0.05$ for a one-tailed test.)

(High background noise level (95dB(A)) - total response time for nine stimulus directions: thirteen subjects x two listening conditions

(nothing in ears, and earmuffs over ears);

Wilcoxon matched-pairs signed-ranks test;

N = 13, T = 14.5, p = 0.01 for a one-tailed test.)

3. Localisation of Warning Shouts

Total Angular Error

Eight of the twenty-one fettlers estimated the direction of all of the fifty-four warning shouts that were presented to them. Eleven of the eighteen office employees estimated the direction of all fifty-four warning shouts.

The total angular error made in each combination of background noise level and listening condition by each of the ninetten subjects is detailed in Table. 16 . Each cell in Table 16 represents the sum of the errors at each of the nine stimulus positions.

In the lower background noise level no significant differences were found between the total angular error made by subjects from the two groups:

(Mann-Whitney U Tests (Siegel, 1956) - differences between total angular error made by subjects in fettler and office employee groups in the lower noise level (75dB(A)): fettler group $n_1 = 8$;

office employee group $n_2 = 11$:

Unoccluded ears: $R_1 = 74$, $R_2 = 116$, $U = 50$, $Z = 0.5$,

$p > 0.6$ for a two-tailed test.

Earplugs in ears: $R_1 = 80$, $R_2 = 110$, $U = 44$,

$Z = 0$, $p \simeq 1.0$ for a two-tailed test.

Earmuffs over ears: $R_1 = 73$, $R_2 = 117$, $U = 51$,

$Z = 0.6$, $p > 0.5$ for a two-tailed test.)

Results for the two subject groups have therefore not been analysed separately. An analysis of the total angular error for the lower background noise level indicated that hearing protectors significantly increased the total error made by the subjects.

(Friedman's non-parametric two-way analysis of variance - total angular error in low background noise level: nineteen subjects x three listening conditions; $Xr^2 = 7.7$, $df = 2$, $p = 0.02$ )

Both earplugs and earmuffs significantly increased the error but earmuffs were significantly worse than earplugs.

(Total angular error in low background noise level: nineteen subjects x two listening conditions; Wilcoxon matched-pairs signed-ranks tests:

No hearing protectors compared with earmuffs:

$N = 19$, $T = 30$, $p < 0.005$ for a one-tailed test.

No hearing protectors compared with earplugs:

$N = 19$, $T = 52.5$, $p < 0.05$ for a one-tailed test.

Earplugs compared with earmuffs: $N = 19$, $T = 61$,

$0.10 > p > 0.05$ for a one-tailed test.)

As can be seen from Table 16, the total angular error made by office employees appeared to be greater than that made by fettlers when they wore earmuffs in the high background noise level. Although the performance of the two groups was not significantly different when they wore earplugs or used unoccluded ears.

(Mann-Whitney U tests - differences between total angular error made by subjects in fettler and office employee groups in the higher background noise level 95dB(A): fettler group $n_1 = 8$, office employee group $n_2 = 11$;

Unoccluded ears: $R_1 = 69$, $R_2 = 121$, $U = 55$, $Z = 0.9$, $p > 0.3$ for a two-tailed test.

Earplugs in ears: $R_1 = 94$, $R_2 = 96$, $U = 30$, $Z = -1.2$, $p > 0.2$ for a two-tailed test.

Earmuffs over ears: $R_1 = 45$, $R_2 = 145$, $U = 9$, $Z = -2.9$, $p < 0.04$ for a two-tailed test.)

The results for the fettler and office employee groups have therefore been analysed separately for the higher background noise level to study the effects produced by hearing protectors.

Listening condition had a significant effect on total angular error for the office employees in the high background noise level but the data are less conclusive about

the effect of listening condition for the fettlers.

(Friedman's non-parametric analyses of variance - total angular error in high background noise level: office employee group of eleven subjects x three listening conditions; $Xr^2 = 13.6$, df = 2, $p < 0.005$; fettler group of eight subjects x three listening conditions; $Xr^2 = 3.25$, df = 2, $p \simeq 0.2$.)

Office employees made significantly more errors when they wore earmuffs than when they wore earplugs or did not wear hearing protectors. The earplugs did not significantly affect the total error made by the office employees.

(Total angular error in the high background noise level: eleven office employees x two listening conditions; Wilcoxon matched-pairs signed-ranks tests.

No hearing protectors compared with earmuffs, N = 11, T = 0, $p < 0.005$ for a one-tailed test.

No hearing protectors compared with earplugs, N = 11, T = 50, $p \gg 0.05$ for a one-tailed test.

Earplugs compared with earmuffs, N = 11, T = 1, $p < 0.005$ for a one-tailed test.)

The difference between the mean angular error for the two subject groups when earmuffs were worn in the higher

background noise level was quite striking. The habitually noise-exposed fettlers - who had also had some experience of wearing earmuffs - appeared to be less affected by the earmuffs.

In figure 25 the angular error made by each of nineteen subjects in the reduced sample (eleven office employees and eight fettlers) have been plotted against their hearing levels ($HL_{\overline{0.512346}}$). Subjects with good hearing appear to make more errors when wearing earmuffs than do subjects with poorer hearing when they attempt to localise against the higher background noise level. A Spearman's rank correlation coefficient confirmed this view:

(total angular error compared with average hearing level: nineteen subjects; Spearman's rank correlation coefficient $r_s = 0.53$, $p < 0.05$ for a two-tailed test for negative correlation.)

Although in the low background noise level the fettlers appeared to be less affected than were the office employees, the difference is small and as is shown in Figure 26 , the hearing level does not appear to correlate with total angular error.

(total angular error compared with average hearing level: nineteen subjects; Spearman's rank correlation coefficient $r_s = 0.078$, $p > 0.2$ for a two-tailed test for negative correlation.)

The mean response errors for the office employee group are tabulated in Table 17; the errors are classified by stimulus position, listening condition and background noise level.

The mean response errors for the fettler group are tabulated in Table 18.

4. Localisation of Warning Shouts

Contralateral Responses

In the earlier studies with localisation of impacts (chapter 3) contralateral responses were easily discernible because subjects were forced to choose between six loudspeaker positions - a response was either to the same side of the median plane as the stimulus or it was an obvious confusion between left and right.

In the experiments with warning shouts the subjects were given a free choice to respond at any angular position on the response diagrams (Figure 18).

Any system for classifying responses as contralateral must, therefore, take into account the error inherent in the use of the response diagrams. Otherwise errors in marking the response diagrams might be classified as contralateral responses.

The region which encompassed 95 percent of the visual control responses at the two visual stimulus position 0 and 4 (ie.

median plane positions infront and behind the subject) are illustrated in Figure 27.

Responses from the warning shout experiments have been classified as contralateral responses if they were put to the wrong side of the median plane outside the region of uncertainty. Examples of the classification system are also illustrated in Figure 27.

The system of classifying contralateral responses should under-estimate rather than over-estimate the number of such responses because the region of uncertainty used for stimulus position 4 was drawn on the basis of errors in the visual control experiment in which the subject had to turn to locate the light - it is likely that the uncertainty region (95 percent confidence limits) for the positioning of auditory responses would be far narrower probably of similar magnitude to position 0. The probability that a response would be incorrectly classifiedas a confusion between left and right would, therefore, be less than $p = 0.025$.

The number of contralateral responses made by each of the subjects in the fettler group are classified by background noise level and listening condition in Table 19 ; the number of contralateral responses made by office employees are tabulated in Table 20.

Earmuffs produced significantly more contralateral responses

than were made with unoccluded ears, or with earplugs, by the office employees in the higher background noise level. There were no significant differences between the numbers of contralateral responses made by the office employee group when wearing earplugs or when no hearing protectors were worn.

(Friedman's non-parametric two-way analysis of variance - number of contralateral responses produced by office employees in high background noise level : nineteen subjects x three listening conditions; $Xr^2 = 10.5$, df = 2, $p < 0.005$.

Wilcoxon matched-pairs signed-ranks tests - number of contralateral responses produced by office employees in high background noise level: nineteen subjects x two listening conditions;

No hearing protectors compared with earmuffs; N = 14, T = 17, $p < 0.025$ for a one-tailed test.

Earplugs compared with earmuffs; N = 16, T = 9, $p < 0.005$ for a one-tailed test.

No hearing protectors compared with earplugs: N = 7, T = 7.5, $p \gg 0.05$.)

A Friedman's analysis of variance on the contralateral responses for the fettler group in the high background noise level failed to show a significant effect from listening

condition.

(Friedman's non-parametric two-way analysis of variance - number of contralateral responses produced by fettlers in high background noise level: twenty-one subjects x three listening conditions; $Xr^2 = 4.3$, df = 2, $0.1 < p < 0.2$.)

However, it is hardly surprising that earmuffs were not shown to have a significant effect by the analysis because many stimuli were missed completely by the fettlers when they wore earmuffs in the high background noise level. Therefore the fettler subject group has been, for the purposes of the contralateral response analysis, reduced to those fettlers (indicated in Table 19 ) who did not miss shouts other than those from directly infront and behind. Stimuli from directly infront and behind could not produce contralateral responses.

An analysis of the contralateral responses for the reduced group of fettlers again failed to show significant evidence of an effect brought about by the wearing of hearing protectors in the higher background noise level.

(Friedman's non-parametric two-way analysis of variance - number of contralateral responses made by fettlers in high background noise level: thirteen subjects x three listening conditions, $Xr^2 = 2.9$, df = 2, $p > 0.25$.)

However, fettlers may not necessarily be free from the increase in contralateral responses detected with office employees because no significant difference could be detected between the effects of hearing protectors on the two groups.

(Mann-Whitney U Tests - differences between numbers of contralateral responses made by subjects in fettler and office employee groups in the higher background noise level (95dB(A)); fettler group $n_1 = 13$, office employee group $n_2 = 18$;

Earplugs in ears: $R_1 = 235$, $R_2 = 261$, $U = 90$,

$Z = 1.3$, $p > 0.18$ for a two-tailed test,

Earmuffs over ears: $R_1 = 194$, $R_2 = 302$, $U = 131$,

$Z = 0.6$, $p > 0.5$ for a two-tailed test.)

However, inclusion of the fettlers who missed shouts in the analysis suggests that fettlers were more affected by earplugs than were office employees but it must be remembered that the existence of an overall effect from listening conditions was not established during the Friedman's analysis of variance for the fettlers.

The distributions of contralateral responses among the stimulus positions are illustrated in Figure 28 . The distributions for the three listening conditions are displayed separately; the totals for each stimulus position include both higher and lower background noise levels. Figure 28

clearly demonstrates that many of the contralateral responses involved errors of high magnitude.

5. Localisation of Warning Shouts

Angular Errors Greater than 30 Degrees

In the previous studies of localisation with impact noises the configuration of loudspeakers used resulted in angular errors of less than thirty degrees being classified as correct responses. The results of the experiments with warning shouts have therefore been analysed for angular errors greater than thirty degrees to facilitate comparisons with previous studies.

The total numbers of errors in excess of thirty degrees are detailed for each subject under each of the listening conditions for both low and high background noise levels in Table 21 for office employees and Table 22 for fettlers. Failure to respond to a warning shout has been recorded as an error in excess of thirty degrees.

For the group of office employees the hearing protectors were found to significantly increase the number of errors in the low background noise level.

(Friedman's non-parametric two-way analysis of variance - errors greater than $30^{o}$ in low background noise level: nineteen subjects x three listening conditions, $Xr^{2} = 7.6$, $df = 2$, $p < 0.05$.)

(Wilcoxon matched-pairs signed-ranks tests - errors greater than $30^{o}$ in low background noise level: nineteen subjects x two listening conditions; No hearing protectors compared with earmuffs: $N = 17$, $T = 27.5$, $p < 0.01$ for a one-tailed test; No hearing protectors compared with earplugs: $N = 12$, $T = 9.5$, $p < 0.01$ for a one-tailed test.)

The difference between the effects of earmuffs and earplugs for the office employees in low background noise was not shown to be significant.

(Earmuffs compared with earplugs: $N = 16$, $T = 50.3$ $p >> 0.05$ for a one-tailed test.)

Listening condition was also found to significantly affect the office employees in the high background noise level.

(Friedman's non-parametric two-way analysis of variance - errors greater than $30^{o}$ in high background noise level: nineteen subjects x three listening conditions; $Xr^2 = 6.8$, $df = 2$, $p < 0.05$.)

Earmuffs increased the number of errors:

(Wilcoxon matched-pairs signed-ranks tests - errors greater than $30^{o}$ in high background noise level: nineteen subjects x two listening conditions; No hearing protectors compared with earmuffs: $N = 15$, $T = 21$, $p < 0.025$ for a one-tailed test.

No hearing protectors compared with earplugs:

$N = 17$, $T = 62$, $p \gg 0.05$ for a one-tailed test.)

But earmuffs produced significantly more errors greater than thirty degrees than did earplugs:

(Wilcoxon matched-pairs signed-ranks test - errors greater than $30^{o}$ in high background noise level: nineteen subjects x two listening conditions; earplugs and earmuffs: $N = 15$, $T = 8$, $p < 0.005$ for a one-tailed test.)

Analyses of the results for the fettlers did not show that listening condition had a significant overall effect on the errors of greater than thirty degrees in either low or high background noise levels; pair comparisons have therefore not been made:

(Friedman's non-parametric two-way analysis of variance - errors greater than $30^{o}$: twenty-one subjects x three listening conditions; low background noise level: $Xr^2 = 2.3$, $df = 2$, $p > 0.3$; high background noise level: $Xr^2 = 4.0$, $df = 2$, $p > 0.15$.)

The average numbers of responses that involved errors greater than thirty degrees are also shown in Tables 21 and 22, for every combination of listening condition and background noise level for both subject groups.

Analysis of the differences between the subject groups did not show the presence of a significant difference:

(Mann-Whitney U test - errors greater than 30° in unoccluded condition x two subject groups: office employees $n_1 = 19$, fettlers $n_2 = 21$; $R_1 = 347$, $R_2 = 388$, $U = 242$, $Z = 1.5$ (corrected for ties) $p > 0.15$ for a two-tailed test.)

Discussion - Perception of Warning Shouts

The experiments at the foundry were planned to investigate the effect of hearing protectors on the localisation of warning shouts. However, during the experiments in which the fettlers were required to determine the direction of the shouts in high background noise levels many shouts were missed completely when the fettlers wore earmuffs. Sixteen percent of the warning shouts were missed by the fettlers when they wore earmuffs. They also missed a few shouts when they were without hearing protectors and when they had glass down earplugs in their ears; approximately three percent were missed with unoccluded ears and five percent with earplugs. The office employees missed approximately two percent of the warning shouts in each of the three listening conditions.

Some of the warning shouts were missed from each of the stimulus positions by the fettlers wearing earmuffs. In

contrast, when the fettlers did not wear hearing protectors or wore earplugs, they missed warning shouts that originated at or near the median plane infront or behind them. Similarly, the office employees whether unprotected or wearing earplugs or earmuffs missed warning shouts that originated at or near the median plane.

When earmuffs were not being worn the warning shouts that were missed usually came from behind; this was probably a function of the added attenuation provided by the pinnae for sounds originating from behind the head that has been discussed by Nordlund (1962).

A statistically significant correlation was found between the number of warning shouts that were missed by wearers of earmuffs in the higher background noise level and the hearing level of the wearers; a finding which adds weight to the concern expressed by Coles and Rice (1965) about the hazardous situations that may arise when persons with severe hearing losses wear high attenuation hearing protection.

Response Time

The results from the analysis of time taken to complete the localisation task confirmed the impression gained during earlier localisation experiments that the wearing of earmuffs can increase the response time. Earmuffs were shown to

increase the time taken to respond to the warning shout in both high and low background noise levels. The average response time in the unoccluded condition varied with stimulus position and the signal to noise ratio between approximately 2.8 seconds and 3.8 seconds. When earmuffs were worn the average response time varied between 3.3 seconds and 4.2 seconds. In the high background noise level (95dB(A)), office employees responded more slowly than in the low background noise level (75dB(A)). This effect was present in all listening conditions, ie. unoccluded ears, earplugs, earmuffs. The fettlers were probably similarly affected by the reduction in signal to noise level when localising the shout. However, the statistical analysis showed that the increase noted during the experiment would have had an approximately ten percent likelihood of occuring by chance. The effect of lowering signal to noise ratio may have been demonstrated less conclusively for the fettlers due to them having missed so many more warning shouts. Response time varied with stimulus position. On average, subjects appeared to take longer to respond to shouts which originated near the median plane than to sounds which originated to their right or left. For example in the low background noise level the average time taken to respond to a warning shout originating directly to the right of the subject was 2.9 seconds when no hearing

protectors were worn, whereas the average time taken to respond to warning shouts from directly behind was 3.3 seconds, ie. approximately fourteen percent more time than for the more easily localised shout from directly to the side.

In the high background noise level the time taken to respond to shouts directly to the right of the subject was 3.3 seconds in the unoccluded condition, ie. a fourteen percent increase in response time.

The increase in response time resulting from the wearing of earmuffs was in general less than the effect produced by the twenty decibel reduction in signal to noise ratio. The average response time for the unoccluded condition in low background noise level was 3.1 seconds; this was increased to 3.2 seconds when earmuffs were worn, and 3.3 seconds when the signal to noise ratio was reduced by twenty decibels and the ears unoccluded.

Earplugs were not shown to significantly affect response time, but neither were their effects shown to differ significantly from those of earmuffs.

Total Angular Error

Hearing protectors increased the total angular error of both office employees and fettlers in the low background noise level. The average error per response with unoccluded ears in low background noise level (75dB(A)) was 35 degrees.

This was increased to 40 degrees by earplugs and to 45 degrees by earmuffs. Earmuffs effectively increased the average error by thirty percent from the unoccluded condition, whereas earplugs increased the error by fifteen percent. Decreasing the signal to noise ratio by twenty decibels in the unoccluded condition increased the average error to 55 degrees; an increase of fifty-seven percent. Angular error was found to vary with stimulus position; the higher angular errors were associated with stimuli from near the median plane. The average angular error for shouts originating directly to the right of the subject for unoccluded ears in the low background noise level was 11 degrees compared with 60 degrees for sound originating directly infront of the subject or 64 degrees for shouts from directly behind the subject.

Decreasing the signal to noise ratio by twenty decibels increased the average error for unoccluded ears to 31 degrees for shouts from directly to the right and 117 degrees for shouts from directly infront. In the high background noise level the average error for shouts from directly behind decreased to 51 degrees. This may have been because subjects were less sure of the direction of the warning shout in the high background noise level and made the "safest guess", a phenomenon which has been observed before; (Stevens and Newman, 1936).

The wearing of earmuffs also increased the total error made by the office employees in the high background noise level. The average error per response for the office employees in the high background noise level was 57 degrees without hearing protectors and 82 degrees when earmuffs were worn. Earplugs were not shown to have a significant effect on total angular error.

The fettlers were not affected by earmuffs to the same degree as were the office employees: average response error for office employees wearing earmuffs in high background noise level was 82 degrees; average response error for fettlers wearing earmuffs in high background noise level was 60 degrees. A significant negative correlation was found between hearing level and angular error made whilst wearing earmuffs; subjects with high hearing losses appeared to be less affected by the earmuffs than were subjects with more normal hearing.

The average response error for the fettlers in the low signal to noise ratio with unoccluded ears was 52 degrees, whereas when earplugs and earmuffs were worn the average response error was 61 degrees and 60 degrees respectively. However, statistical analysis showed that these differences between listening conditions for the fettlers in high background noise level had a twenty percent probability of occurring by chance.

Confusions Between Left and Right

Results were analysed for confusions between left and right of the median plane. Responses that were placed to the side of the median plane from which the stimulus had not originated were classified as contralateral responses.

The two subject groups made very few contralateral responses when listening for the warning shout in the low background noise level (75dB(A)). There were no contralateral responses with unoccluded ears in the lower background noise level; one contralateral response out of a total of 351 stimulus presentations when earplugs were worn; and 9 out of the 351 stimulus presentations when earmuffs were worn.

In the high background noise level more contralateral responses were made and, for the office employees, earmuffs were shown to increase the number of contralateral responses. In the unoccluded condition the office employees made 11 contralateral responses out of 162 stimulus presentations (7 percent); when they wore earplugs the number of contralateral responses (5) was not significantly different from the unoccluded condition (3 percent); when earmuffs were worn, 30 contralateral responses were made (18 percent).

The total numbers of contralateral responses made by the fettlers in the high background noise level were: 11 contralateral responses with unoccluded ears; 16 contralateral

responses with earplugs; 29 contralateral responses with earmuffs. These correspond to 6 percent, 8 percent and 15 percent respectively. However, statistical analyses showed that these differences between listening conditions for fettlers in high background noise level had about a 15 percent probability of occurring by chance.

Contralateral responses were not restricted to stimuli that came from near the median plane - many of the responses that were put to the wrong side of the median plane originated directly or almost directly to the right or left of the subjects.

Errors Greater than Thirty Degrees

To facilitate comparisons with other work the numbers of errors of greater than thirty degrees of arc were analysed separately. Hearing protectors were not shown to affect the number of errors greater than thirty degrees for the fettlers in either 75dB(A) or 95dB(A) background noise level.

In the low background noise level earplugs and earmuffs were shown to increase the number of greater than thirty degree errors for office employees: 31 percent of the responses made without hearing protection constituted errors greater than thirty degrees; when earplugs were worn, there were 43 percent; when earmuffs were worn, there were 47 percent. The

difference between earplugs and earmuffs conditions was not statistically significant.

In the high background noise level listening condition was also shown to increase the number of greater than thirty degree errors for the office employee group: 59 percent of the responses in the unoccluded condition were errors greater than thirty degrees; when earplugs were worn the proportion was 56 percent; when earmuffs were worn 70 percent of the responses were errors in excess of thirty degrees.

In Table 23 the results from these analyses have been compared with the results from other localisation experiments.

The localisation task in the 75dB(A) background noise level was apparently about as difficult as the task of localising impact noise in the presence of white noise described in Chapter 3. The loss in localisation ability when earmuffs were worn was approximately 19 percent for the shouted warnings in low background noise level - this compared with the 18 percent loss in localisation ability when earmuffs were worn during the impact noise experiment.

As can be seen from Table 23 the localisation of warning shouts in the 95dB(A) background noise level probably represented the most difficult conditions under which localisation ability has yet been tested.

Differences between the Effects of Hearing Protectors on Perception and Localisation for Office Employees and Fettlers

The most striking difference between the effects of hearing protectors on the two groups was the correlation found between the hearing level of the subjects and the number of warning shouts that were missed when earmuffs were worn in the high background noise level; subjects with poorer hearing missed more warning shouts.

The total error made by the fettlers under the three listening conditions in the lower background noise level did not differ significantly from that made by office employees. However, when higher background noise levels were encountered the office employees were more severely affected than were the fettlers by the earmuffs. A significant correlation was found between the hearing level of the subjects and the total angular error they made when wearing earmuffs in the high background noise level. The increase in confusions between left and right brought about by the wearing of earmuffs was also more readily demonstrated with office employees than with the fettler group.

Although no significant difference could be demonstrated between the ability of office employees and fettlers to determine the direction of the shouts to within thirty degrees of the stimulus position, in low or high background noise,

hearing protectors were shown to significantly increase the errors made by office employees, although they did not significantly increase the fettlers' errors.

General

In the foundry experiments subjects were able to move their heads whilst determining the direction of the warning shout. Some of the subjects were observed without their knowledge whilst they tackled the experiments. The subjects usually instinctively moved their head to face the direction from which they thought the warning shout came. The impression gained after observing subjects was that the slower responses coincided with occasions when the subjects did not instinctively turn to face the warning shout.

The average time taken to respond to stimuli from all positions have been compared with the average response error for the respective stimulus positions in Figure 29 for the office employees in the low noise level and three listening conditions. Slow responses appear to be associated with large angular errors:

(Spearman's rank correlation coefficient: office employees in low background noise level for three listening conditions and nine stimulus positions; average response error x average response time: $r_s = 0.8$, $p < 0.02$ for a two-tailed test of positive correlation.)

It would appear that the subjects do not improve their localisation accuracy by taking longer to respond. This is not surprising when one remembers that the stimulus is of very short duration. If the stimulus had been a continuous or repeated sound the subjects might have been able to trade response time and angular error.

Differences between the Effects produced by Earplugs and Earmuffs

An important and relevant question concerning the use of hearing protectors in industry is whether earmuffs affect the flow of information to the wearer more seriously than earplugs.

As has already been discussed, earmuffs appeared to increase the number of shouts which were missed by the subjects in the high background noise level - however, the effect could have occurred by chance with a probability of between $p = 0.2$ and $p = 0.3$.

The analyses of the responses for the lower background noise level indicated that earmuffs had a greater effect on localisation than did earplugs.

Earmuffs produced more total angular error for both fettlers and office employees than did earplugs in the lower background noise level. Earmuffs produced more contralateral responses than did earplugs for the office employees in the high background noise level. Earmuffs also produced a higher number of

errors of greater than thirty degrees for the office employee group in the high background noise level than were produced by the wearing of earplugs.

The results indicated that the earmuffs produce errors of greater magnitude than are produced by earplugs. The larger the errors produced by hearing protectors, the greater would be their potential for endangering the life of the wearer.

## Conclusions

The foundry studies of the localisation of warning shouts have provided further evidence that earmuffs are likely to adversely affect the localisation ability of the wearer in high levels of background noise.

The group of office employees, who had no previous experience of wearing earmuffs and had not been habitually exposed to intense noise at work, were less accurate and took longer to respond to the warning shout when they wore earmuffs than when they had unoccluded ears. Earmuffs produced these adverse effects both when the shout could be clearly heard above the background noise level of 75dB(A) and when the shout could barely be heard above the background noise level of 95dB(A).

Similarly, the group of fettlers, all of whom had some experience of wearing hearing protectors and had been habitually exposed to high levels of noise in the foundry, were less

accurate and took longer to respond when they wore earmuffs than when they had unoccluded ears in the noise level of 75dB(A). Many of the fettlers were, of course, exhibiting noise-induced deafness.

Earmuffs were shown to affect localisation more than earplugs.

The localisation ability of the office employees was affected more by the wearing of earmuffs than by earplugs in both the 75dB(A) and 95dB(A) background noise levels. In the lower background noise level the average angular localisation error was increased from 35 degrees per response with unoccluded ears to 39 degrees by earplugs and to 47 degrees by earmuffs.

In the higher background noise level the average angular localisation error was increased from 57 degrees with unoccluded ears to 82 degrees by earmuffs; whereas earplugs did not increase the average error per response. Earmuffs also increased the number of confusions between left and right of the median plane although wearing earplugs was not shown to affect the number of this type of error. Earmuffs also increased the number of errors greater than 30 degrees but earplugs did not.

The localisation ability of the fettlers was affected

more by earmuffs than by earplugs in the 75dB(A) background noise level. The average angular localisation error increased from 34 degrees with unoccluded ears to 40 degrees with earplugs and to 43 degrees with earmuffs.

In the higher background noise level a significant correlation was found between hearing level and average localisation error per response for each subject; subjects with hearing losses were less affected than subjects with normal hearing. However, there was also a significant correlation between the number of warning shouts that a subject missed and his hearing level; subjects with hearing losses missed more shouts than subjects with normal hearing.

It can be concluded from the results presented in this chapter that earmuffs are likely to adversely affect the localisation ability of people asked to wear earmuffs in industry. It can also be concluded that earplugs can be expected to produce less of an adverse effect on localisation than would be produced by earmuffs.

# CHAPTER FIVE

## OTHER EVIDENCE WHICH SUGGESTS THAT HEARING PROTECTORS MAY ADVERSELY AFFECT THE SAFETY OF THE WEARER

### Introduction

Many potential wearers of hearing protectors express concern that the protectors will put them at greater danger. Some foundrymen, who have worn hearing protectors, have given this as their reason for ceasing to use the protectors. Sugden (1967) reported that only about 30 percent of a group of thirty foundrymen were wearing protection regularly six weeks after the introduction of glass down earplugs. Three had stopped using the protection because they felt "too deaf and quite unsafe" in the environment of overhead and hand-operated cranes and stacking trucks. One of the foundrymen was prepared to wear his protection when working on the night-shift because the general level of activity in the foundry was then less intense than during the day-shift. Sugden concluded that there was a high incidence of what he considered were valid objections to the wearing of the protectors. I have also received many complaints from a range of industries that hearing protectors make the wearer feel less safe.

However, the evidence has been anecdotal and often, though not always, presented as a justification for not wearing the hearing protectors.

The effects which hearing protectors have on localisation ability - discussed in Chapters 3 and 4 - may account for some of the concern shown by hearing protector users. Impaired directional hearing is, however, not the only detrimental effect ascribed to hearing protectors.

Some people complain of feeling isolated when they wear hearing protectors; others complain of loss of balance; or say they worry about the perception of warning sounds or their ability to interpret sounds which they use to monitor industrial processes. Howell and Martin (1975) reported that many industrial workers complain that verbal communication is impeded by hearing protectors and Ivergard and Nicholl (1976) reported studies which indicated that earmuffs were not worn because they made it more difficult to hear speech.

## Perception of Warning and Monitoring Sounds

Murphy and colleagues (1972) have warned about the dangers of missing warning signals such as "roof talk" in mines.

Although there appear to have been no studies of the effects of hearing protectors on warning signals Murphy and colleagues report that the drafting committee for the United States Coal Mine Health and Safety Act of 1969 was sufficiently concerned to include a specific requirement in Section 206 to ensure that miners would not be required to wear hearing protectors which would affect their ability to hear warning

sounds.

It is not surprising that the effects of hearing protectors on the perception of warning or monitoring sounds have not been studied in the past, because these effects would be very difficult to test. The sounds which are used by industrial workers to warn them of danger, or which they use to monitor processes, are seldom easy to isolate or reproduce. Often these sounds convey no meaning to the inexperienced listener and may be indistinguishable from the background noise to the untrained ear. For example, it would be very difficult to test the claims made by forestry power-saw operators that hearing protectors make them less safe. Dunn (1970) in his study of accident risks in power-saw operation used a structured interview with 25 sawyers to explore their reasons for not wearing earmuffs. He reported that the first and most common reason given, apart from discomfort, suggested that the earmuffs affected the auditory information used by the sawyer: rustling, creaking and snapping of branches. Dunn also reported a second reason given for not wearing earmuffs which they described as a feeling of being "cut off" or generally not being able to hear properly.

Many of the people who need to make use of hearing protectors in industry have been exposed to noise unprotected

for many years. These people may have elevated thresholds due to the effects of noise exposure and presbyacusis. Coles and Rice (1965) warned that although the risk of increasing the danger exists, in theory, for all men working in noise when they wear hearing protection, the danger would almost certainly be greater for those with pre-existing hearing losses. They predicted that people with severe noise-induced hearing losses would have reduced ability to perceive indicator sounds against a background because such sounds would usually be identified by their high-frequency content. They thought that this ability would be further impaired by the wearing of earplugs, because earplugs provide higher attenuation at high frequencies than at low frequencies. Earmuffs also provide higher attenuation of high frequency sounds and could be expected to have a similar effect.

Burns (1973), in his advice on selection of hearing protectors, counsels caution lest the wearing of hearing protectors introduces dangers far worse than impaired hearing. In particular, Burns expresses concern for the older wearers of hearing protectors and previously noise-exposed who may have elevated thresholds which would be further elevated by the additional attenuation provided by hearing protectors. It could be concluded from this that high attenuation earmuffs would constitute a greater danger than earplugs, or earmuffs

of lower attenuation.

Speech Communication

In contrast to the perception of warning sounds, the effect of hearing protectors on speech communication has been the subject of numerous studies.

Kryter (1946) reported that in sound pressure levels above about 80dB under reverberant conditions, articulation scores from monosyllabic word lists for people wearing V51-R earplugs were as high or higher than for listening with unoccluded ears. Further work by Pollack (1957) indicated that the wearing of V51-R earplugs caused no reduction in articulation score for noise levels above 90dB SPL and that a distinct advantage could be gained by wearing earplugs in noise levels in excess of 110dB SPL. The findings were further supported by Williams and colleagues (1971) who showed that V51-R earplugs produced higher articulation scores for rotary winged aircraft passengers both in flight and in the laboratory when they were exposed to aircraft flight noise at sound levels between 110dB SPL and 115dB SPL.

However, the evidence which predicted no adverse effects for normal hearing subjects, or perhaps slight beneficial effects, came mostly from experiments in which the subjects listened to recorded speech or talkers who were not wearing hearing protectors. It has long been recognised that hearing

protectors worn in high noise levels reduce the voice level of the wearer: Kryter (1946), Acton (1967) and Coles (1969).

A talker hears his own voice partly by air conduction and partly by bone conduction and he adjusts his own voice level to overcome the background noise which he hears mainly by air conduction. When the talker wears hearing protectors the external noise is attenuated but due to bone conduction the protectors will have little effect on the loudness of his own voice. The talker may therefore decrease his voice level because there seems to be less noise to overcome.

Ali (1974) showed that earplugs and earmuffs can reduce the equivalent-continuous sound level produced by a speaker's voice by as much as five A-weighted decibels.

Ali's subjects were required to repeat a sentence against a broad-band industrial noise. Howell and Martin (1975) in similar studies used lists of monosyllabic words and two broad-band background noises one with a fast rising spectrum and the other a fast falling spectrum.

Howell and Martin found that earmuffs reduced the wearer's voice level by an average of 2.7 decibels and the earplugs reduced the voice level by an average of 4.2 decibels. They also found that the wearing of hearing protectors caused no degradation in intelligibility for persons listening to speech in noise levels above 85dB(A) but they found that the

composite effect when both talker and listener wore earplugs or earmuffs was an overall reduction in speech intelligibility. In a noise level of 93dB SPL the mean intelligibility score from monosyllabic word tests was 50 percent when both listener and talker had unoccluded ears; 43 percent when they both wore earmuffs, and 30 percent when they both wore earplugs.

Howell and Martin used inexperienced subjects for their experiments. The subjects did not know that they were talking quietly when they wore hearing protectors. It could be argued that experienced wearers of hearing protectors would be able to overcome the attenuating effect which the hearing protectors have on voice levels. With this objective in view, advice is often given to hearing protector users that they should attempt to speak more loudly, eg. Burns (1973). However, Howell and Martin concluded from their results that the quality of the speech was also affected by the wearing of hearing protectors. There is at present no evidence to show that advising users of hearing protectors to speak more loudly does overcome the effect of the hearing protectors.

The studies of Howell and Martin, as with most other studies of the effects of hearing protectors on speech communication,were confined to subjects with normal hearing.

Coles and Rice (1965) studied the effects of earplugs on the reception of monosyllabic words by twelve normal and

twelve impaired hearing subjects with moderate or severe high-tone hearing losses. They concluded that people with high-tone hearing losses are likely to have a greater impairment of speech by wearing earplugs than do persons with normal hearing and the extra impairment will occur in the quieter intervals between successive noises.

The recent experiments of Lindeman and van Leeuwen (1973) have confirmed the predictions of Coles and Rice. Lindeman and van Leeuwen studied the effects of earmuffs on the intelligibility of monosyllabic words presented from a loudspeaker against a background noise level of 80 decibels*. A total of 537 workers with varying degrees of occupational deafness participated in the experiments which took place at ten industrial plants in the Netherlands. Earmuffs were shown to reduce the intelligibility of speech for subjects with severe hearing losses; however, the extent of the effect cannot easily be quantified from the data presented by Lindeman and van Leeuwen.

* decibel scale not specified.

## Conclusions

A considerable amount of evidence exists to suggest that hearing protectors may make the wearer feel less safe. However, much of the evidence has come from users who have been reluctant to wear hearing protectors and it could be

argued that their concern for personal safety may have been in part a rationalisation for not wearing the protectors.

However, reports in the literature suggest that people with elevated thresholds resulting from presbyacusis and noise exposure may be in greater danger when they wear hearing protectors. They may experience difficulty perceiving warning or monitoring sounds and may have greater difficulty communicating when they wear hearing protectors.

# CHAPTER SIX

# OPTIMISING THE SELECTION OF HEARING PROTECTION

## Introduction

The current methods for the selection of hearing protectors have been discussed in Chapter 2. Persons charged with the responsibility for selecting hearing protectors would normally use one of the methods to calculate the A-weighted attenuations that individual types of hearing protectors would be likely to afford the wearers against particular noise spectra. The selection methods enable the selector to reject those hearing protectors which would be unlikely to reduce the wearer's exposure to below the current recommended limit for noise exposure. However, the selection methods do not specify an upper limit for the attenuation that should be sought for a particular application.

The application of the selection criterion narrows the choice of hearing protectors to those which are capable in theory of protecting the wearer but the person responsible for selecting hearing protectors may be left with a choice between many types of earplugs and earmuffs all of which are theoretically capable of providing protection.

The selector might well assume that all hearing protectors capable of reducing the wearer's daily noise exposure below the recommended limit would be equally desirable. The selector might in practice exhibit an understandable tendency to provide

the maximum protection possible and consequently select a protector which would reduce the wearer's daily noise exposure well below the recommended limit.

Some selectors may choose to select the hearing protector which is capable of reducing the instantaneous noise level below the recommended limit for daily exposure to noise rather than choose a lower attenuating protector which would adequately reduce the wearer's daily noise exposure to below the recommended limit. Indeed, selectors of hearing protectors in the United Kingdom may be encouraged to select high attenuation hearing protectors by the advice given them in the Code of Practice (Department of Employment, 1972):

> "Ear protectors should normally be specified so that the sound level at the user's ear is always effectively reduced to 90dB(A) or less.
>
> Exceptionally, where exposure is for short periods only, protectors may be chosen so that the assumed value of Leq* is reduced to 90dB(A) or less. However, this procedure should be avoided where possible, and if adopted it is particularly important to ensure that the exposure to noise is effectively controlled, and that the ear protectors are correctly used."

* Leq = equivalent continuous sound level which in the course of an eight-hour period would cause the same A-weighted sound energy to be received as that due to the actual sound over the actual working day.

However, the unrestrained search for high attenuation may have a positively detrimental effect on the safety of the user of the hearing protectors.

Hearing protectors should be provided to reduce the risk of occupational deafness not the instantaneous sound levels per se. The choice between alternative types of hearing protectors should be made on the basis of their relative abilities to reduce the risk of occupational deafness and clearly the decision-making must be tempered by the possibility that the hearing protectors may adversely affect the safety of the wearers.

## The Reduction in Risk Provided in Theory by Hearing Protectors Chosen According to the Selection Methods

I have shown (Else, 1971) that hearing protectors provide vastly different A-weighted reductions in different noise spectra. The selection methods which have been developed to estimate the reduction that would be afforded by a particular type of hearing protector against a particular frequency spectrum are discussed in Appendix I. The selection methods are shown to have inherent errors besides the errors associated with the attenuation data themselves which have been discussed at length elsewhere: eg. Shaw and Yates (1946), Hershkowitz and Levine (1957), Weinreb and Touger (1960), Waugh (1970), Michael and Bolka (1971), Howell and Martin (1973).

However, the errors were shown to be minor by comparison

with the consequences of not calculating the A-weighted reduction for each individual noise spectrum.

The procedure of applying attenuation estimates to each octave band within a frequency spectrum is incorporated in all current selection methods but opinions differ about the centile from the attenuation distribution that should be used in the calculations.

In 1969 Coles reported that mean attenuation data were widely used in the calculations. This procedure would of course have resulted in the exposure of approximately 50 percent of the exposed population to levels in excess of the recommended limits even if they had worn the hearing protectors. It is therefore not surprising that the use of attenuation estimates drawn from lower centiles from the attenuation distributions was advocated - Coles (1969) recommended the use of the mean attenuation minus one or two standard deviations.

The Code of Practice issued a few years later recommended the use of either lower quartile attenuation estimates or the mean attenuation minus one standard deviation. This could result in exposure beyond the recommended limit for between approximately 16 percent and 25 percent of the wearers. Consequently, the Draft Australian Code of Practice for Hearing Conservation (Standards Association of Australia, 1972) incorporated the use of the mean minus one and a half standard deviations as the attenuation estimate. The stated aim

of the Australian selection method was the reduction of level for ninety percent of the wearers of hearing protectors.

Similarly, the Occupational Safety and Health Administration in the United States are being obliged to consider the use of mean minus two standard deviations for attenuation estimates (Shaw, 1976).

If the pressure has resulted from a desire to ensure that no greater risk is accepted for hearing protector users than would be acceptable for unprotected exposure, then a vital consideration has been omitted because the calculation of residual risks for wearers of hearing protectors is essentially a problem of convolving distributions - the dose-risk distribution and the attenuation-population distribution.

A computer model was used in Chapter 2 to convolve the dose-risk and attenuation-population distributions. Application of the model suggested that the use of valid lower quartile attenuation estimates in the selection of hearing protectors should effectively reduce the risk of occupational deafness* for the wearers to the level accepted for unprotected exposure to noise.

The use of mean minus one and a half standard deviations, or mean minus two standard deviations, in the selection methods would imply that a lower risk of occupational deafness could be accepted for wearers of hearing protectors than would be accepted

* The criterion used in the computer analyses was the risk of exceeding $25 dB HL_{\overline{0.512}}$.

for unprotected exposure to noise. This would result in the selection of hearing protectors of higher attenuation but would it result in greater reductions in risk of occupational deafness in practice?

The Reduction in Risk Provided in Practice

The selection methods assume implicitly that the chosen hearing protectors will be worn by all the population at risk during the whole time that the users are exposed to high levels of noise. This assumption is unlikely to be valid.

In the Annual Report of the Chief Inspector of Factories for 1974 the results of two surveys of hearing protector usage are described (Department of Employment, 1975). One hundred factories were visited in 1971 before the introduction of the Code of Practice (Department of Employment, 1972). Five hundred and sixteen employees were found to have been provided with hearing protectors but only twenty-one were using them at the time of the survey.

The factories were revisited during 1973 and 1974 two years after the introduction of the Code of Practice. It was found that the total number of hearing protectors provided in the factories had greatly increased (1100) but very few employees were using the protectors (125).

The results from the surveys imply that no more than twelve percent of the hearing protectors were being worn but it is

probable that many of the companies within the survey were achieving a much higher usage of hearing protectors. Unfortunately, no attempt was made by the Factory Inspectorate in their surveys to determine whether those wearing hearing protectors wore them for the total exposure duration. I have shown that the reduction in sound level predicted by the selection methods could only be achieved if the hearing protectors were worn for the total duration of exposure (Else, 1973).

Unfortunately, the importance of wearing hearing protectors for a very high proportion of the exposure duration may not be adequately conveyed to the wearers. In Chapter 2 it was shown that the most conscientious wearers of hearing protectors in a foundry were not aware of the importance of the short periods during which they removed their hearing protectors. They were provided with earmuffs which should in theory have reduced the equivalent-continuous sound level by 24dB(A) but in practice they could not have received more than between 14dB(A) and 18dB(A) reduction in equivalent-continuous sound level because they took the hearing protectors off for about twenty minutes in approximately four hours. They removed the protectors when they were not producing noise but they were still exposed to the noise levels about 90dB(A) from other processes.

The degree of protection provided in practice by hearing protectors depends on the percentage of the exposure duration

for which the hearing protectors are actually worn; protectors which in theory provide high attenuation are relatively more sensitive to the short periods of non-use than are protectors which in theory provide low attenuation (Figure 30).

For example, the protection provided by a hearing protector which reduced the instantaneous sound level by 30dB(A) would be reduced by 10dB(A) if the protector was removed for one percent of the exposure duration. Whereas the protection provided by a 10dB(A) hearing protector would be reduced by less than 0.5dB(A) if it was removed for one percent of the exposure duration.

In theory, hearing protectors provide widely different A-weighted reductions according to the noise spectra. However, the protection they provide may not differ so widely.

The attenuation data for glass down earplugs have been applied to the sample of 2640 industrial noise spectra (Appendix V) to study the distribution of reductions in equivalent-continuous sound levels that would result if the earplugs were not worn for the total duration of noise exposure. The distributions of this protection with noise spectra are shown in Figure 31 ; the distributions that would result from earplugs being worn for seventy-five percent, ninety percent, ninety-five percent, ninety-nine percent and one hundred percent of the exposure duration are illustrated.

The difference between the protection provided against the

fifth centile of noise spectra and the ninety-fifth centile of noise spectra is 11dB(A) if the earplugs are worn throughout the duration of noise exposure. However, the difference between the protection provided against the fifth and ninety-fifth centiles reduces to: 7dB(A) if they are worn for ninety-five percent of the exposure; 5dB(A) if the are worn for ninety percent of the exposure; and 2dB(A) if they are worn for only seventy-five percent of the exposure duration.

The selection methods also assume implicitly that the attenuation measured in the laboratory with test subjects will be realised in practice. There are many reasons why the theoretical attenuation may not be achieved in practice, quite apart from any acoustical inadequacies in the attenuation test methods.

The attenuation data obtained from attenuation tests on small samples of young white males may be poor predictors of the attenuation provided to the population of white male industrial workers, or to women, or men and women of other ethnic groups.

The attenuation data will also be poor predictors of the attenuation provided in practice for industrial workers unless the fitting procedures during the laboratory attenuation tests adequately simulate the fitting procedures used in industry. I have not been able to find any published data on the effects of fitting procedures used in industry but it is commonly agreed that in the laboratory setting differences in fitting

procedures account for a significant proportion of the variation in attenuation estimates for the same protectors measured at different laboratories by the same methods (Martin, 1971).

Similarly, the attenuation data are unlikely to predict the protection afforded to users who wear spectacles, goggles or respirators, all of which may interfere with the seal of an earmuff to the head.

New hearing protectors are used during most laboratory attenuation tests; the data from these tests are likely to over-estimate the attenuation provided in practice unless the hearing protectors are very well maintained, or disposable.

The headbands on earmuffs in use in industry may be of reduced tension because of normal use, or because the users have attempted to make the protectors more comfortable to wear.

The seals on earmuffs in use in industry may be less compliant than those which were on the protectors under test in the laboratory. In Figure 32 the seals of earmuffs that were being worn by a foundryman in a fettling shop are compared with the equivalent seals when new. The foundryman had been using the earmuffs for three months. It is obviously very unlikely that he was in practice being provided with the attenuation that the earmuffs theoretically afforded him.

Clearly in practice the reduction in risk provided by hearing protectors of high attenuation may not be greater than

the reductions provided by lower attenuation hearing protectors unless they are: worn for a very high proportion of the exposure duration; maintained frequently; and the users trained to fit them correctly.

## Conclusions

It is apparent from the foregoing discussion that the reduction in the risk of occupational deafness provided by a hearing protector in practice is not solely determined by the attenuation as tested under laboratory conditions with new hearing protectors. The reduction in risk afforded by hearing protectors in practice will also depend upon:

(i) the percentage of exposure time for which the hearing protectors are worn;

(ii) how well the protectors are maintained;

(iii) how well the protectors are fitted.

Hearing protectors which provide the highest attenuation in theory may not provide the greatest reduction in risk of occupational deafness in practice. Indeed, an uncomfortable high attenuation hearing protector which is not worn før a high percentage of the exposure may provide less protection from the risk of occupational deafness than will a consistently worn comfortable low attenuation protector.

It can be concluded that the benefits to be gained by providing hearing protectors of higher attenuation than would

be consistent with reducing the risk of occupational deafness to the level accepted for unprotected exposure are minimal.

However, evidence has been presented in Chapters 4 and 5 which suggests that high attenuation hearing protectors may produce greater deleterious effects on the safety of the wearer than low attenuation protectors.

Unfortunately, the attenuation provided by a hearing protector and the physical form that it takes are confounding variables. It is difficult to separate the effects produced by the high attenuation provided by earmuffs from the effects produced by the covering of the pinnae; because in the past, high attenuation has been the sole province of the earmuff, whilst low attenuation has been the sole province of the earplug. But without doubt, high attenuation earmuffs have been shown to affect localisation ability more seriously than do earplugs (Chapters 3 and 4).

High attenuation protectors could be expected to have greater deleterious effects on the perception of sounds by persons with elevated thresholds. The experiments in the foundry described in Chapter 4 suggested that earmuffs would be likely to affect the perception of warning shouts more than would the wearing of earplugs for noise-exposed foundrymen.

It was shown in Chapter 2 that high attenuation hearing protectors would be unlikely to produce significantly greater reductions in noise immission level than low attenuation

protectors for people who had been exposed unprotected for some years.

Little evidence can be presented in favour of selecting hearing protectors of higher attenuation than is strictly necessary to reduce the risk of occupational deafness to the accepted level, apart from the natural desire that noise exposures should be reduced as much as possible. Howell and Martin (1975) presented evidence to suggest that earmuffs when worn by talker and listener could have less effect on speech communication than lower attenuating earplugs. But the advantage of the earmuffs was not a result of their higher attenuation but rather the absence of the occlusion effect and apparent increase in bone conduction which accompanies the wearing of earplugs.

However, Howell and Martin thought that the hearing protectors may have less serious effects on speech communication in practice because conversation would be between people experienced in conversing in noisy industrial environments and often conversations would be face to face which would provide added visual cues. Another point not discussed by Howell and Martin is that industrial users of hearing protectors should be advised to speak more loudly when they wear hearing protectors and in most circumstances in which they converse whilst wearing hearing protectors, they will be constantly receiving feedback to remind them that they should speak more loudly. The subjects

in the experiment of Howell and Martin, however, were unaware that hearing protectors were reducing their voice levels.

At present we have no evidence that the effects of hearing protectors on voice level cannot be overcome by training. However, Noble has reported (private communication, 1976) that major attempts to train two users to localise whilst wearing earmuffs failed, although they did respond to training with earplugs. This is an aspect of the use of hearing protectors which requires further research.

The balance of the arguments, therefore, appears to indicate that selectors of hearing protectors should be advised to choose the lowest attenuation device that is likely to reduce in practice the risk of occupational deafness to the level accepted for unprotected exposure to noise. At present, the selection of hearing protectors can be optimised by ensuring that the lowest attenuation hearing protectors are chosen which on the basis of calculations with lower quartile attenuation data can be shown to reduce the equivalent-continuous sound level to the recommended limit and with which a high degree of usage can be achieved.

The key to protection, therefore, is to be found in continuous use of hearing protectors by the whole of the work force during their entire period of exposure to noise at work - the attenuation provided by the protectors needs to be adequate but no more than adequate in any particular circumstance. The

notion that attenuation should be an optimum value rather than the maximum attainable value has important implications for hearing protector designers who should as a result of these findings be able to concentrate their efforts on the comfort and acceptability of hearing protectors with, I hope, correspondingly beneficial effects on the degree of utilisation by workpeople with noisy work.

# CHAPTER SEVEN

## CONCLUSIONS

A computer model has been used to estimate the risk of occupational deafness for noise-exposed populations who wear hearing protectors. The model has been used to show that high attenuation hearing protectors are unlikely to reduce the risk of occupational deafness by a greater amount than could be achieved with low attenuation hearing protectors under the following conditions:

(i) If the high attenuation hearing protectors are not worn for the full duration of exposure to noise then lower attenuating protectors may provide greater protection* if these are worn for the total duration of exposure

(ii) If the high attenuation hearing protectors are not worn by a proportion of the noise-exposed population then a greater reduction in risk* might be afforded by a lower attenuation protector if that protector were worn by a higher proportion of the population

(iii) If the population has been exposed to noise for many years prior to the provision of hearing protectors then the reduction in risk provided by high attenuation protectors may be indistinguishable

*these are terms which are specifically defined in the text

from the reduction provided by low attenuation protectors.

The computer model highlighted the importance of selecting hearing protectors which will be worn by a high percentage of a noise-exposed population for a high percentage of their exposure duration. The model also highlighted the importance of providing hearing protectors immediately noise exposure commences.

Laboratory studies of the localisation of impact noise in quiet and in an 85dB(A) background of white noise showed that earmuffs reduced the localisation ability of inexperienced subjects. Earplugs were not shown to affect localisation of the impact noise.

Experiments at a foundry with normal-hearing office employees and noise-exposed foundrymen who had some experience of wearing hearing protectors showed that although earplugs reduced the ability of the wearer to determine the direction of warning shouts in both 75dB(A) and 95dB(A) levels of pink noise, earmuffs produced more total angular error and more confusions between left and right.

The benefits to be gained by providing hearing protectors of higher attenuation than would be required to reduce the

risk of occupational deafness to the level accepted for unprotected exposure to noise appear to be small ~~;~~ the disadvantages in terms of affecting localisation may be considerable. My conclusion is that an optimum value of attenuation should be sought during the selection of hearing protectors, not a maximum value.

It is my recommendation on the basis of the evidence available at present that the hearing protectors with the lowest attenuation should be chosen which, on the basis of calculation with lower quartile attenuation data, can be shown to reduce the equivalent-continuous sound level to 90dB(A)* and with which a high degree of usage can be achieved.

The process of optimising the selection of hearing protectors should be reviewed in the light of:

(i) new evidence regarding the effects of hearing protectors on personal safety;

(ii) changes in noise exposure criteria;

(iii) closer definition of the residual risk of hearing loss for hearing protector wearers becoming available.

*or the current recommended limit

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