Contents

Introduction

This report presents the results of a Coal Services Pty Ltd Health and Safety Trust funded project titled "*Working Safely with Hearing Loss*". The project arose from the need to develop a reliable procedure for testing whether underground coal miners with a high degree of hearing loss could hear adequately in the work environment for safety purposes. It is vitally important that all workers be able to respond appropriately to warnings during an emergency situation. A worker who has significant loss of hearing, as defined through audiometric testing, is assumed to be less capable of hearing warnings and is therefore considered a risk to himself and others.

While this would certainly be the case for a profoundly deaf person or a person who has lost part of their hearing through a sudden trauma, workers who have sustained 'industrial deafness' over a long period of time partially adapt to the condition and can often hear much better during normal conversation than their audiograms would suggest. This adaptation is due to the greater conscious effort to listen and the use of visual cues such as lip-reading and observing the speaker's body language. These visual cues are generally not presented underground and the true effect of the hearing loss is uncertain.

Another important factor affecting the audibility of shouted warnings is the presence of high background noise levels. Even people with little or no hearing loss find it difficult to hear speech in a noisy environment. This project therefore investigates the ability of work-aged people with hearing loss to hear verbal commands in a noisy, underground environment. No attempt is made to determine the absolute level to which the underground environment affects speech intelligibility. Rather, the focus is on the reduced hearing ability of the 'industrially deaf' worker compared to that of a worker with little or no loss of hearing.

Glossary of acoustical terms

This section of the report aims to explain the meanings of relevant terms in clear language. The terms are not listed alphabetically. Rather, they are listed in a logical order, roughly following the order in which they appear in the report. Several other terms will be defined in the text as they appear.

Frequency

When an object vibrates in air it emits minute pressure waves that travel outward at the speed of sound (around 340m/s). The distance between adjacent pressure waves is inversely proportional to the vibration speed of the object: small distances for quick vibrations and larger distances for slower vibrations. With all pressure waves traveling at the same speed, the quicker vibrations will cause more pressure waves to pass a given point in a given time period than a slower one will. The number of acoustic pressure fluctuations to pass a point in one second is referred to as sound frequency and its unit is the Hertz (Hz).

The human ear can hear sound frequencies from as low as 20 Hz up to as high as 20000 Hz. This is referred to as the 'audible spectrum' of sounds. For practical purposes, our recognition of different sound frequencies may be termed "pitch perception". Low pitched sounds (such as a bass drum) indicate low-frequency acoustic pressure vibrations in the air, whereas high-pitched sounds (say, a piccolo) indicate high frequency vibrations.

Third-octave band frequencies

Most vibrating bodies emit a large range of frequencies all traveling outward together and individual clear 'tones' are rarely identifiable. When measuring sound, it is often necessary to break the audible spectrum up into frequency 'bands' to give a clearer picture of where the acoustic energy is concentrated: is the noise mainly low-pitched, high-pitched or a broad spread of frequencies?

The most basic break-down of the audible spectrum is into 'octave bands', where octave refers to a doubling of frequency. The central frequencies of the ten octave bands covering the audible spectrum are 31.5 Hz, 63 Hz, 125 Hz, 250 Hz, 500 Hz, 1000 Hz, 2000 Hz, 4000 Hz, 8000 Hz and 16000 Hz. When broken down into octave bands, sounds at 430 Hz, 504, Hz and 580 Hz will all be lumped together into the octave band centred on 500 Hz.

For even greater refinement (as is required in this study) each octave band is broken down into three third-octave bands. As an example, the octave band centred on 500 Hz incorporates three third-octave bands with centre frequencies at 400 Hz, 500 Hz and 630 Hz. Sounds at 430 Hz, 504, Hz and 580 Hz will now belong in these different third-octave bands.

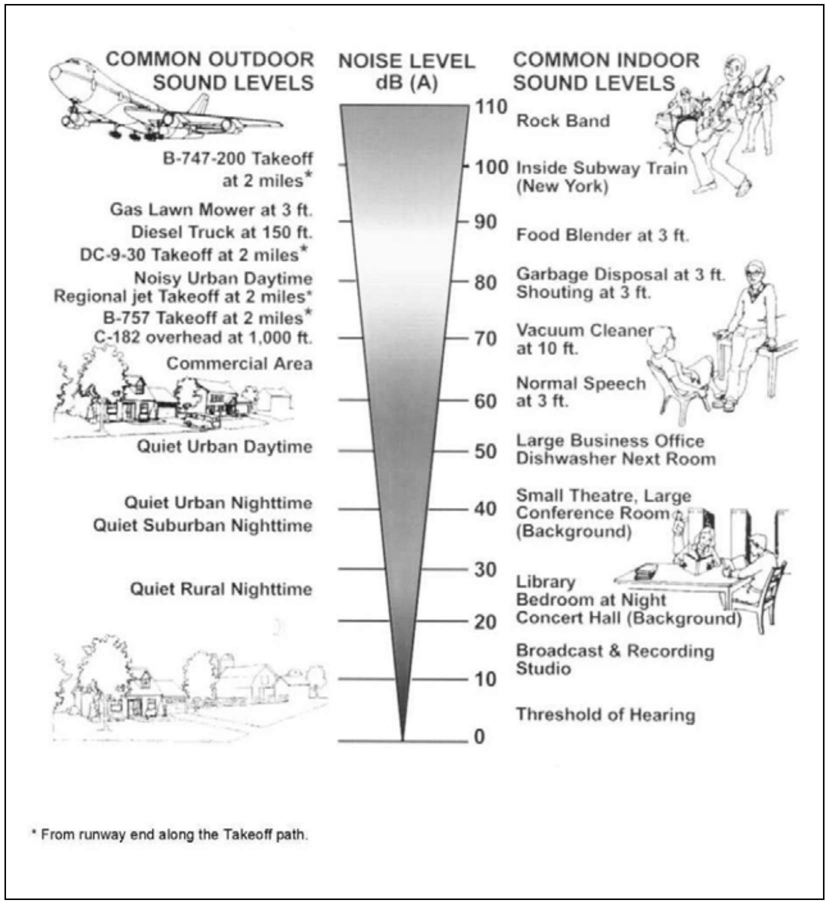
Decibels
The hearing mechanism is responsive to a range of acoustic pressure fluctuations in the air ranging from around one millionth of a Pascal (Pa) to one hundred Pascals. Such a huge range of pressures would be unwieldy and impractical to express in Pa units. The audible range of acoustic pressures is therefore compressed logarithmically to give Sound Pressure Level (SPL) as follows:

$$SPL = 10\log_{10}(p/p_0)^2 = 20\log_{10}(p/p_0)$$

where p_o is a reference pressure equal to 20 μPa. The unit of SPL is the decibel (dB). By substitution in the above equation, we see that an acoustic pressure of 20 μPa is equal to 0 dB and a pressure of 1 Pa is equal to 94 dB. The conversion from Pa to dB therefore enables the range of audible sounds to be conveniently expressed as numbers ranging from 0 dB (theoretical threshold of hearing) to 120 dB (pain threshold). Figure 1 shows the decibel levels of some familiar sounds.

FIGURE 1:

Decibel levels of familiar sounds



Hearing threshold level

This is the quietest level that the person being tested can hear at a given sound frequency during a pure-tone audiometric test. As an example, a perfectly healthy ear can just make out a 500 Hz tone at 18 dB [1].

Threshold shift

If a person's hearing becomes damaged, their hearing threshold will occur at higher levels. In the above example, if the person being tested could not hear a 500 Hz tone quieter than 28 dB, then they are said to have experienced a threshold shift of 10 dB. Threshold shift may be permanent, as in a sensorineural hearing loss, or temporary, as often occurs for a few days after exposure to loud sounds.

Percentage loss of hearing (PLH)
The percentage of hearing loss is calculated from the measured threshold shifts at each of the frequencies assessable under the relevant Standard [2]. These frequencies are 500 Hz, 1000 Hz, 1500 Hz, 2000 Hz and 4000 Hz. The PLH's at each frequency are added together to give the total PLH. From the above example, the 10 dB threshold shift at 500 Hz corresponds to a 2.1% PLH for that ear.

Monaural hearing loss
This is the total PLH calculated from audiometric testing of one ear only. A PLH value would usually be calculated for each ear when a person is being fitted for hearing aids or being assessed for a degenerative hearing condition in either ear.

Binaural hearing loss
A person's total PLH is dependent upon the differences between threshold shifts for both ears at the given frequencies. If, in the example above, the person's other ear had a hearing threshold level of 35 dB at 500 Hz, then their calculated binaural PLH at that frequency would be 2.8%.

Presbyacusis
Presbyacusis is the natural loss of hearing that accompanies aging, and is not due to noise exposure. It is a sensorineural hearing loss that cannot be corrected. Approximately 15% of those 55-64 years of age, 30% of those 65-74 years of age, and 40% of those over 75 years of age have a naturally-occurring hearing loss that affects communication. Presbyacusis can be adjusted for when determining the amount of hearing loss attributable to noise exposure.

Basics of the auditory system

The human hearing mechanism is one of the most complex and sensitive devices found in nature, and some of its components are not yet fully understood. When functioning correctly, it can detect and amplify the impacts of individual air molecules (this is what we hear when cupping a sea shell to the ear). It is responsive to a range of vibration frequencies spanning 10 octaves, from 20 Hz to 20000 Hz, and can distinguish between two tones separated by only a few Hertz.

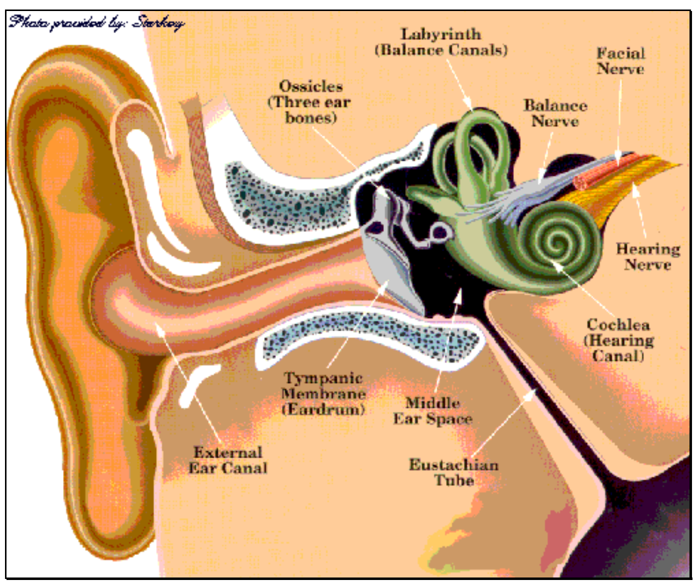
To put this into perspective, a concert piano has an 8-octave range from a bass note of approximately 55 Hz to a high note of over 5000 Hz, yet two adjacent keys produce noticeably different sounds. The loudest audible sound (pain threshold at approximately 140 dB) has a sound pressure ten million times that of the quietest sound.

Figure 2 shows the anatomy of the ear with its three major sections:

- **Outer Ear** – consists of the external ear (pinna) and ear canal;
- **Middle Ear** – starts at the eardrum, behind which is an air filled space containing the three tiny bones that transmit air vibrations to the inner ear; and
- **Inner Ear** – contains the balance canals, cochlea and associated nerves.

FIGURE 2:

Anatomy of the

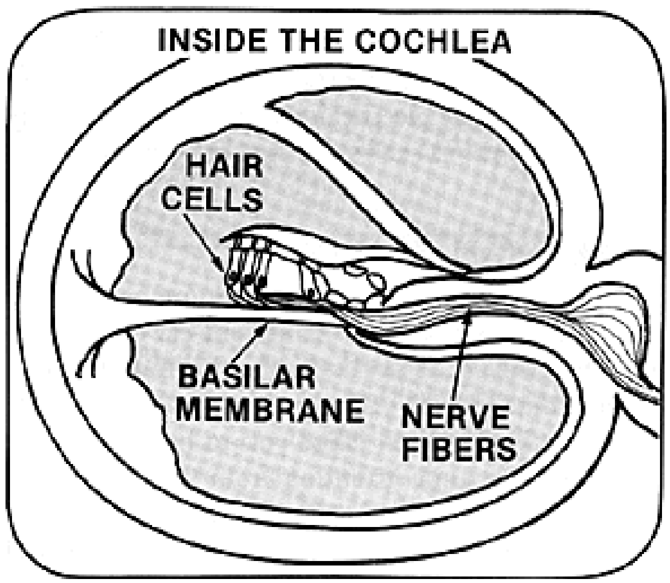


Sound waves enter the ear canal and vibrate the eardrum. These vibrations are transmitted (and amplified by a factor of 3) by tiny bones to the cochlea, which is like a fluid-filled hose rolled up into a spiral.

The cochlea has several membranes running along its length, so that it is more like three hoses wrapped up in a skin. Openings at the end of each individual "hose" allow the fluid pressure to balance out along the length of the coiled-up cochlea. A section through a spiral of the cochlea is shown in Figure 3, illustrating the three chambers separated by membranes.

FIGURE 3:

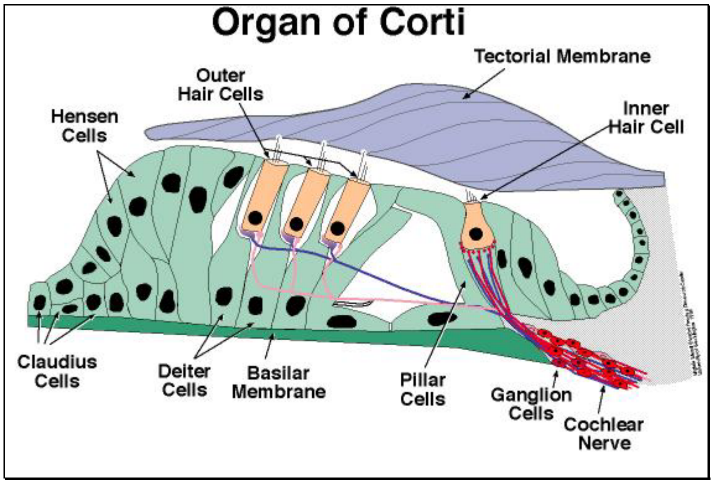
Cross-section through a spiral of



The structure sitting on top of the basilar membrane is called the Organ of Corti, which is shown in greater detail in Figure 4.

FIGURE 4:

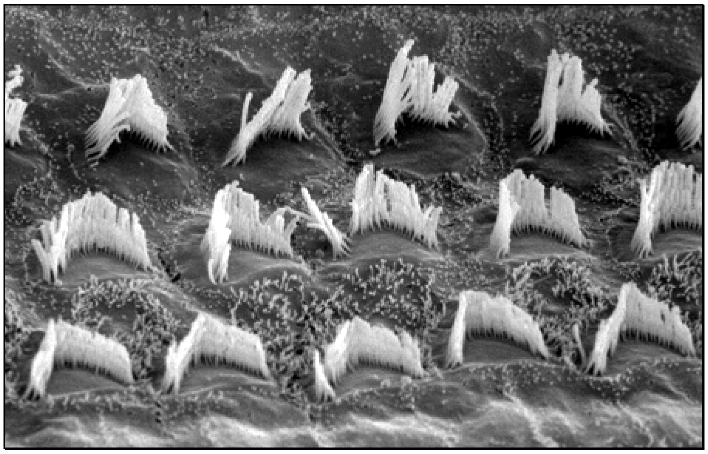
Organ of Corti.



Pressure fluctuations in the lower fluid-filled chamber cause the basilar membrane to vibrate, which in turn causes the hairs (stereocilla) on top of the outer hair cells to rub against the tectorial membrane. Figure 5 shows three layers of stereocilla, as photographed under an electron microscope.

FIGURE 5:

Cochleal hair cells (stereocilla) viewed through an electron microscope. Note the obviously damaged hairs in the back two



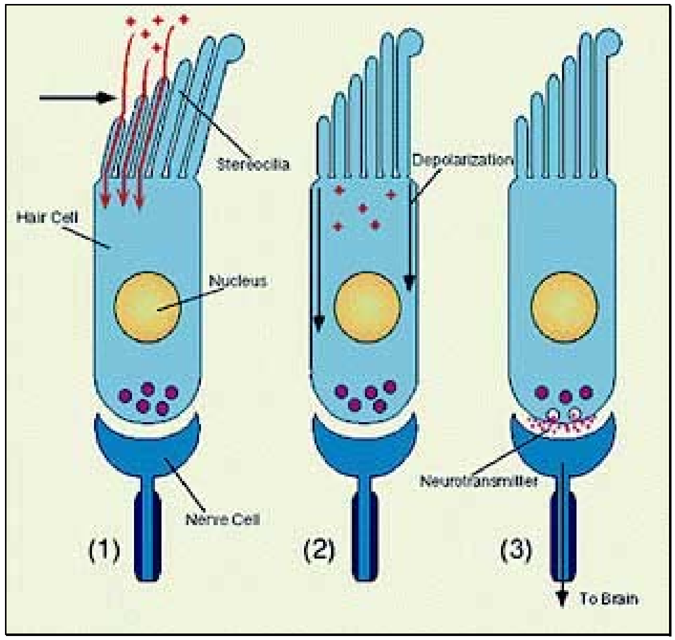
This contact causes the stereocilla to bend and release a small electrical signal, which then causes a momentary elongation or "pumping" of the hair cell. Finally, the pumping hair cells release neurotransmitters at the base, triggering a nerve pulse that is transmitted to the brain via the cochlear nerve for processing, as illustrated in Figure 6.

FIGURE 6:

The hearing transducer:

(1) Hairs bend against the tectorial membrane and release electrical signal;

(2) Hair cell pulses in response to electrical stimulus;



Types of hearing loss

Hearing loss can be categorized according to which part of the auditory system is damaged. There are three basic types of hearing loss: conductive hearing loss; sensorineural hearing loss and central auditory processing disorders.

Conductive hearing loss

Conductive hearing loss occurs when sound is not conducted efficiently through the outer and middle ears, including the ear canal, eardrum and tiny bones (ossicles) of the middle ear, and usually involves a reduction in perceived sound level. Presence of a foreign body; impacted ear wax (cerumen); fluid in the ear associated with colds, allergies, ear infections; or a poorly functioning eustachian tube are all examples of conditions that may cause a conductive hearing loss. This type of hearing loss can often be corrected through medicine or surgery.

Central auditory processing disorder

Central auditory processing disorder (CAPD) occurs when auditory centers of the brain are affected by injury, disease, tumor, heredity or unknown causes. CAPD does not necessarily involve hearing loss, but affects sound localization and lateralisation, auditory discrimination, auditory pattern recognition, the temporal aspects of sound and the ability to deal with degraded and competing acoustic signals. CAPD is often associated with Attention Deficit Disorder (ADD).

Sensorineural hearing loss

Sensorineural hearing loss occurs when there is damage to the inner ear (cochlea) or to the nerve pathways from the inner ear to the brain. This type of hearing loss not only involves a reduction in sound level, but also affects speech understanding. It can be caused by diseases, birth injury, drugs that are toxic to the auditory system, genetic syndromes, noise exposure, viruses, head trauma, ageing and tumors. Sensorineural hearing loss cannot be corrected medically or surgically – it is a permanent loss.

Severity of noise-induced hearing loss

Noise-Induced Hearing Loss (NIHL) is a sensorineural hearing loss caused by the destruction of hair cells (stereocilla) due to prolonged exposure to high noise levels. Being a sensorineural disorder, NIHL cannot be corrected with medicine or surgery. NIHL is classified in various stages from 'slight' to 'profound' depending upon the magnitude of the threshold shift.

Since hearing threshold levels are measured at several frequencies, a person may have differing degrees of hearing loss at different frequencies. The classifications of hearing loss, based on measured threshold levels, are shown in Table 1.

TABLE 1:

Classification of hearing loss severity based on measured

Threshold level, dB	Severity of hearing loss
15 – 25 dB	Slight
25 – 40 dB	Mild
40 – 55 dB	Moderate
55 – 70 dB	Moderately severe
70 – 85 dB	Severe

> 85 dB	Profound

Figure 7 depicts the advancement of hearing loss with exposure time within a group of coal miners from the mid-1900's. The values are presented as hearing loss (averaged over both ears), not threshold level as is the case with modern audiograms, so the bold line at zero represents a threshold level of 15 dB for most frequencies (that is, no hearing loss). Adding 15 dB to all values for frequencies less than 4000 Hz (20 dB for 4000 Hz) in Figure 6 would give the hearing threshold levels.

FIGURE 7:

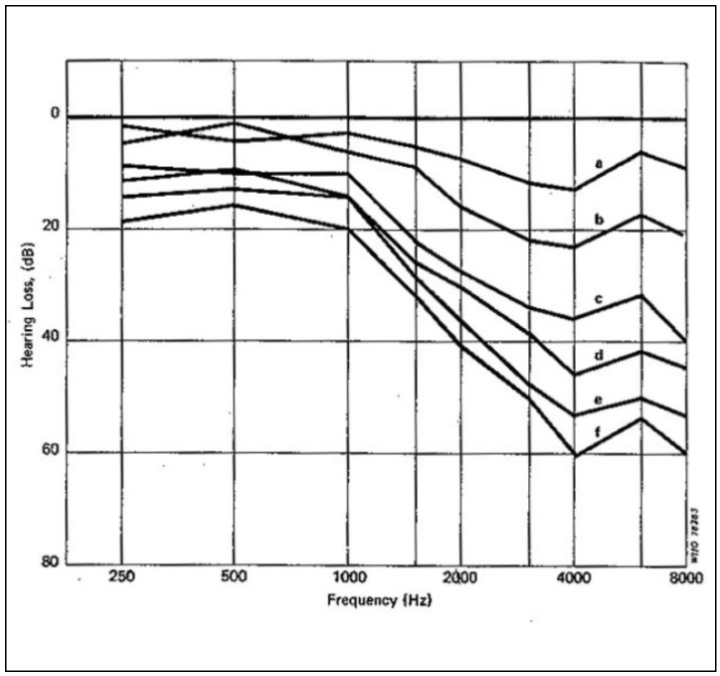
Average hearing loss in a group of miners from the mid-1900's. Exposure time:

a) <1 year;

b) 1-5 years;

c) 6-10 years;

d) 11-20 years;



It is apparent from Figure 7 that a threshold level of 80 dB(A) at 4000 Hz was common in long-time coal miners from the mid-1900's. Table 1 identifies this as a 'severe high frequency hearing loss'. The hearing loss of 20 dB (that is, threshold level of 35 dB) at 1000 Hz in curve *'f'* of Figure 7 represents a 'mild mid-frequency hearing loss'.

Hearing tests in the mining industry

Within the mining industry it is a legislative requirement for mine managers to ensure that employees are medically fit before they are appointed for work, and throughout their time in the industry. Being medically fit includes the ability of the person to adequately hear the commands that may affect their safety or the safety of those around them.

Specific and general medical requirements are stated in Alnewcol No 105, *Joint Coal Board health screening and medical examinations – New South Wales coal mining industry*, selected relevant clauses of which are reproduced below:

Clauses of Alnewcol No 105 referring to

1. HEALTH SCREENING ON ENTRANCE TO THE NSW COAL INDUSTRY

1.1 All new entrants to the coal mining industry must be medically screened and issued with an appropriate certificate by the Board's medical staff before they are permitted to work in the industry.

1.2 The health screening will include a questionnaire, physical examination and such tests as are deemed necessary by the medical staff in the particular case. It will cover previous medical history, present health and symptoms and tests such as eyesight and hearing required by the Regulations.

A set of guidelines to be used by medical staff in evaluating a new entrant is given with the proviso that "The guidelines are not intended as a precise set of rules, but will require interpretation by the medical staff with full knowledge of the individual's situation and the particular job requirements."

2. PERIODIC HEALTH SCREENING

2.2 The frequency of such examinations [periodic health tests] shall be two to three yearly intervals, as far as practicable.

2.3 Each such periodic health screening shall include a standardized history questionnaire and eyesight and hearing tests.

The standard implementation of the above requirements is to test new entrants to the mining industry and then to re-test every 3 years. An informal benchmark has developed by which a worker who returns a hearing test result showing more than 20% binaural hearing loss is not issued with an Eyesight and Hearing Certificate, until such time as the Board's medical personnel are satisfied that the condition poses no great risk to the safety of the individual and his co-workers.

Definition of the Problem

Legislative requirements

Prior to the Coal Mines regulation 1999 the appointment of mining officials, shotfirers and transport operators required individuals to undergo a medical examination at least every three years. Part of this medical examination was to determine whether the person being examined had hearing ability such that they could carry out and undertake their duties effectively.

Under the new Coal Mines Regulation 1999 the requirements are less specific, however. The new Regulation states that the mine manager must be satisfied that mining officials, shotfirers and operators are medically fit before being appointed. The question arose as to how they were going to do this.

A defining case study

During 1999, one hundred and thirty employees at an underground coal mine in the NSW Hunter Valley underwent eyesight and hearing tests as required by legislation under the Coal Mines Regulation (Deputies, Shotfirers and Transport- Underground Mines) 1984 and the Coal Mines Regulation Act 1982. Of those one hundred and thirty employees, fifteen had a binaural hearing loss of more than twenty per cent.

Based on the results of the tests, Eyesight and Hearing Certificates for these fifteen employees were temporarily withheld. The mine then received written advice that such significant hearing loss would most likely '*make the understanding of instructions difficult in an environment with high background noise*' and may place the employees at excessive risk. As a result the mine had fifteen employees who were unfit for work and could not be sent underground.

The mine also received further recommendations including auditing of the first aid records for indications of past incidents that could relate to hearing difficulties, consultation with Supervisors and a practical verbal test to determine if the employee could hear instructions. Unfortunately, this provided no guidelines with which to proceed as a well defined and repeatable test was not available.

The fifteen employees who were affected were immediately informed of the results of their hearing tests. At the outset of the process it was decided that these employees should be actively involved in the development of a practical testing procedure. Consequently they were involved in all meetings and processes as they were developed.

Step One – Benchmarking

The first step was to benchmark/ research what other mines had done. It was found that simple practical verbal tests had been conducted by other mining companies. Testing appeared to have been in the form of giving instructions to the employee in varying work situations to determine how much he could hear.

The problem with this approach was that there were no measurements of any noise levels at the site of testing, hence it was very subjective. If the employee was deemed to have 'passed' the test there was no way of determining how loud the instructions were yelled or called, how much background noise was present and how the background noise may have affected the test. The absence of test reliability was of great concern.

Step Two – Retesting

Of the fifteen employees, eleven were retested (the remaining four were either retiring or leaving the industry by taking redundancy). Of the eleven that were retested, seven remained above twenty per cent binaural hearing loss. On retesting, the other four showed a loss of less than twenty per cent, were issued with Eyesight and Hearing Certificates and subsequently returned to normal duties.

Step Three – Independent testing

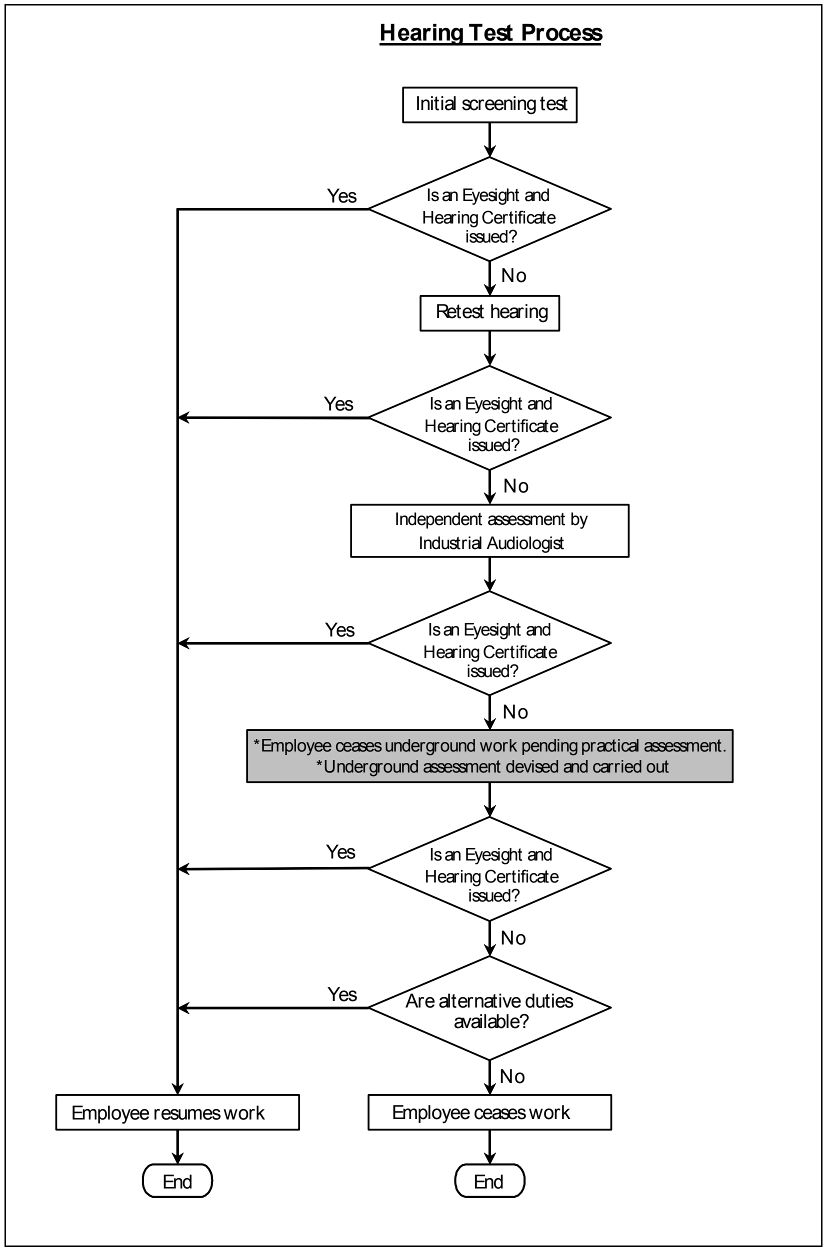
The remaining seven employees were sent for independent testing by an Industrial Audiologist and of these, three were again found to have a binaural hearing loss of more than twenty per cent. The other four were issued with Eyesight and Hearing Certificates as above and returned to normal duties.

Step Four – Underground site assessment

In an attempt to determine if the remaining three were actually safe to work the mine began the development its own underground site assessment procedure. A flow diagram outlining the process followed by the mine is shown in Figure 8.

FIGURE 8:

Process followed by test-case mine to assess workers with



** This step in the process had no clear answer and became the subject of this research project.*

Procedure Development

Practical considerations

In developing a practical test procedure it was considered necessary to address the following issues:

- Validity of the testing procedure. There was a need to develop an underground assessment that was in some way quantifiable and repeatable.

- Noise levels in the underground environment had to be measured at
  - the speaker's location;
  - the listeners' locations; and
  - background noise.

- Intrinsically Safe testing equipment had to be sourced. Safe working procedures for use of these in the underground assessments had to be developed.

- The effect of background noise
  - on those with hearing loss; and
  - on those with minimal hearing loss (ie people who can hear well).

- Consequences of the assessment results. The three individuals who required the underground assessment were very much aware of the issues for them and their ability to work. If their hearing was not adequate for them to be able to gain an Eyesight and Hearing Certificate the following options would apply:
  - alternative duties in the current workplace;

- cease work at the mine; or
- investigate the use of an intrinsically safe hearing aid and continue in their original duties pending successful retesting.

First underground test

A practical hearing test was devised and implemented towards the end of 1999. This led to the issuing of Eyesight and Hearing certificates to one of the three workers, who was able to resume normal duties. Further testing helped to gain certificates for the other two workers and a summary of the procedure was presented at on Occupational Health and Safety Conference [3]. A more complete analysis of those results is presented below.

Background

In order to determine the appropriate assessment methodology, it was initially decided to conduct a 'speech intelligibility' test similar to those conducted in speech studios and auditoria. The test was intended to reveal whether the enclosed, potentially reverberant underground environment had an effect on an individual's ability to discern words, and whether the effect was dependent upon the degree of hearing loss. The proposed test differed from a standard speech intelligibility test in that a high level of background noise would be present.

As with a standard speech intelligibility test, so-called 'Boothroyd' word lists were used. These are short mono-syllable words with consonants at both ends and a vowel sound in the middle, such as FOOT, SHOP and PART.

In addition to the Author of this report, a second 'caller' was chosen from amongst the mine's employees. The only instructions given were to wait approximately ten seconds between calling each word (to give 'listeners' time to write down the words) and to use as much vocal effort as he thought necessary for the listeners to hear him. Seven tests were conducted (each involving ten Boothroyd words) under the following conditions:

- Minimal background noise;
- Caller next to a loud noise source, with
  - Listeners at 10 m, 20 m and 30 m distance; and
- Listeners next to the noise source, with
  - Caller at 10 m, 20 m and 30 m distance.

These configurations were chosen to give various ‘signal-to-noise’ (S/N) ratios. The S/N ratio is the decibel difference between the desired signal and the background noise level. It is positive if the desired signal is louder than the background and negative if the signal is quieter than the background level. In the context of this experiment, S/N is defined for each third-octave band frequency as the difference between the level of the signal in that band and the total background noise level. Because S/N is a function of signal frequency only, it will be denoted S_f/N.

In addition to the worker being tested, two ‘control’ listeners with minimal hearing loss were included so that comparisons could be made, being mindful that with was a ‘comparative’ not ‘absolute’ study of speech audibility.
The assessment required measurement of the background noise and the desirable acoustic signal (speech) at third-octave band resolution. Unfortunately, no certified intrinsically safe (explosion-proof) instrument could be sourced and measurements had to be taken at a distance greater than 100m from the coal face in the non-hazardous zone.

Noise dosimetry conducted at the mine had revealed background noise levels up to 95 dB(A) at the coal face and in the development areas. Similar levels have been found by other researchers [4], [5].

To simulate noise levels at the coal face, a personnel carrier was used as a noise source for the tests. This vehicle produced over 90 dB at a distance of 1 m, with a broad spectrum containing significant energy over the required frequency range from 250 Hz to 4000 Hz.

Measurements were taken at the listener’s ear with a Brüel & Kjær 2260C Investigator precision sound level meter. The instrument was set to A-weighted, fast response and programmed to record third-octave band spectra for each 1-second of measurement.

Each called word was evident as a spike in the time trace. Spectra for the desirable signals (words) were derived from the maximum noise level during the spike and the background level was calculated as the average of the ambient levels immediately before and after each spike.

Preliminary findings

All analysis of results involved making corrections for the listeners' audiometric results. Figure 9 shows the audiogram for the listener with hearing loss (KT) and a base curve to represent the control listeners (IM) and (OM), both of whom were assumed to have no hearing loss.

While this may not be valid, the 'zero-loss' assumption maximized the difference between theoretical perceptual abilities of the test listeners and KT, enabling KT to be compared with a 'perfect' hearer.

FIGURE 9:

Audiogram of test listener 'KT'.

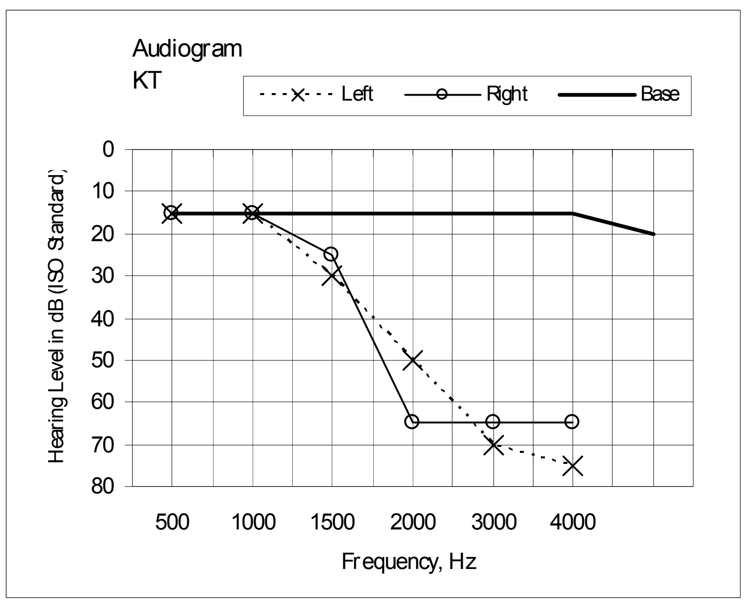
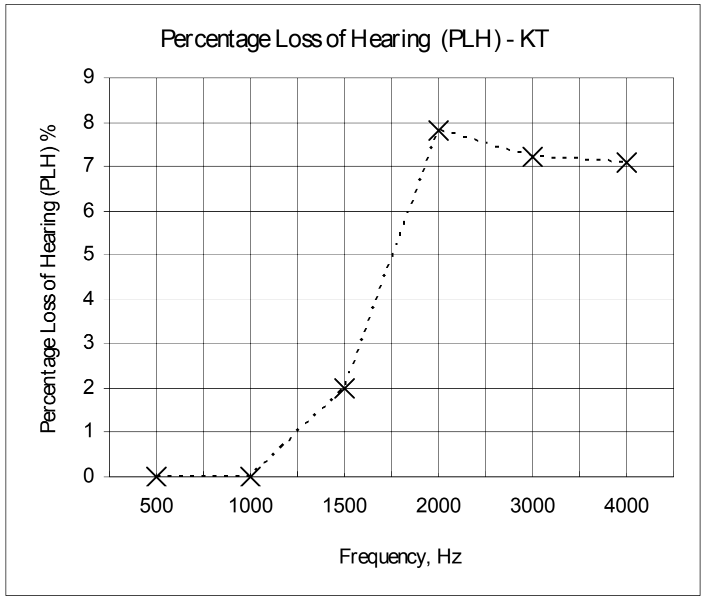


Figure 10 shows calculated binaural percentage loss of hearing (PLH) as a function of frequency, based on the audiogram in Figure 9. No correction for presbyacusis was necessary. The total PLH of 24.1% lead to the initial withholding of an Eyesight and Hearing certificate.

FIGURE 10:

Binaural percentage loss of hearing (PLH) for listener 'KT'.

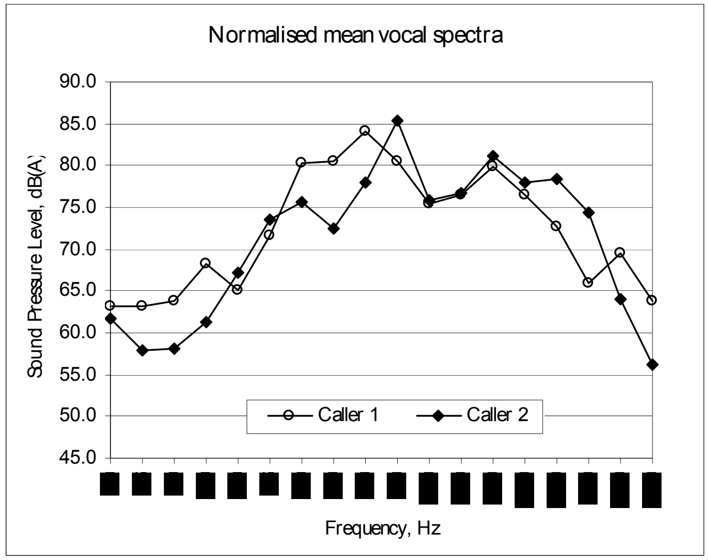


These results show that KT has a relatively minor level of hearing loss (2 % PLH) at frequencies up to 1500 Hz and a much greater loss at frequencies 2000 Hz and above (22.1 % PLH). In order to determine the potential relevance of this to speech perception, the vocal spectra of both callers were calculated from the average of words called when the noise source was turned off (S/N was positive at all frequencies).

Figure 11 shows the resulting spectra at frequencies from 100 Hz to 5000 Hz. The spectra have been normalized to an overall level of 90 dB(A) for ease of comparison. In practice, the miner's voice (Caller 1) was louder than the Author's voice (Caller 2).

FIGURE 11:

Average vocal spectra of Callers 1 and 2. Caller I was a large, middle-aged coal miner and Caller 2 was the Author, who



The spectra in Figure 11 both show two dominant peaks: one centred near 800 Hz and one around 1600 Hz. These spectral shapes did not shift horizontally to different frequencies with varying vocal effort, although the overall 'volume' changed considerably.

The first peak contains most of the 'volume' of the words, emerging 5 dB above the adjacent spike, and represents the central vowel sounds in the Boothroyd words. Caller 1 had a wider spread of frequencies peaking at a lower frequency, indicative of a low, 'gravelly' voice and a more resonant chest cavity. Caller 2's vowel sounds had a 'cleaner' and slightly higher pitched tone with no spread either side of 800 Hz.

Consonant sounds for both callers peaked at 1600 Hz, but Caller 2 had a broader spread of frequencies up to 2500 Hz. It was noted by KT during the tests that Caller 1 seemed to 'drop his 'S' sounds'. This may be reflected in Caller 1's relative absence of vocal energy above 1600 Hz.

Intermediate findings

The mean vocal spectra in Figure 11 suggest that a person needs to be able to hear well at around 800 Hz and 1600 Hz in order to maximize speech perceptibility in the relative absence of background noise. Table 2 summarises the situation for KT, based solely on the above findings.

TABLE 2:

Partitioning of KT's hearing loss across

Frequency range, Hz	Threshold level, dB	Severity of Hearing Loss	PLH, %	Speech component
400 - 800	15	No loss	0	Vowels
800 - 1500	15 - 30	Slight - mild	2	None
1500 - 2500	30 - 65	Mild – moderately severe	8	Consonants
> 2500	65 - 75	Moderately severe - severe	14	None

It is apparent from Table 2 that KT has no loss of hearing at frequencies necessary for hearing the louder vowel sounds in simple words. A mild – moderately severe loss (8 %) at consonant frequencies suggests a reduced ability to discriminate between similar sounding words that differ only in their consonants, such as CART and PATH. The remaining 16 % of hearing loss is at frequencies less critical for speech perception.

The next step in the analysis was to determine S_f/N ratios for both KT and a theoretical non-hearing impaired listener, corresponding to the base line hearing threshold curve in Figure 9.

Measured noise spectra of the desired signals (speech) and the prevailing background noise were both modified by the audiometric results to yield 'perceived' noise levels. This is the signal in the auditory nerve available for processing by the brain after having passed through the physical auditory system.

Correction of the signals was conducted as follows:

1. At each frequency, it was determined whether the threshold level was greater or less than the signal level.
2. If the threshold level was higher, then the signal is inaudible and a value of zero was recorded.
3. If the signal was higher than the threshold level, then the perceived level was taken as the base threshold level plus the difference between the signal and the actual threshold level.

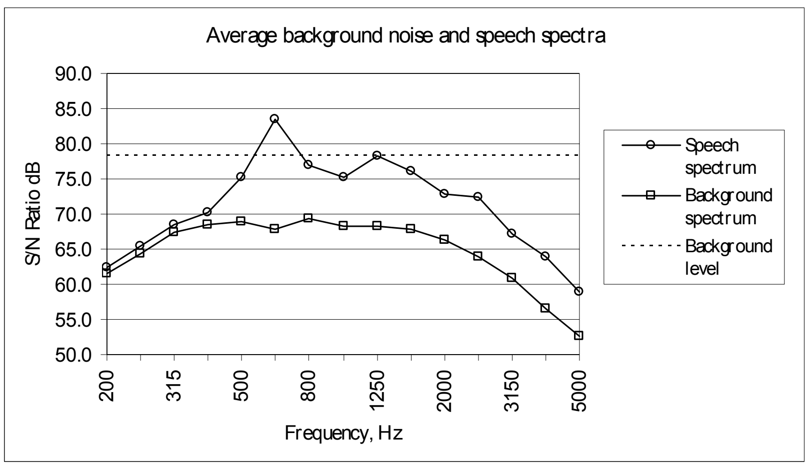
As an example of this last step, consider a signal containing 70 dB(A) at 2000 Hz being presented to KT and the perfect listened (base curve in Figure 9). The 70 dB signal is only 5 dB above the threshold level for KT. It was reasoned that this would be perceptually equivalent to a 20 dB signal being presented to the perfect hearer, whose threshold is 15 dB. The perceived level of the 70 dB(A) signal was therefore taken as 20 dB(A) for KT, at this frequency.

The above process was firstly applied to the background noise spectrum and then to the spectra of test words to provide perceived signal and background noise levels, tailored to the relevant audiometric results. These signals were then compared to yield perceived S_f/N ratios.

Figure 12 shows the measured background noise spectrum, overall background level and average word spectrum for a list of ten Boothroyd words.

FIGURE 12:

Background noise and speech spectra in first

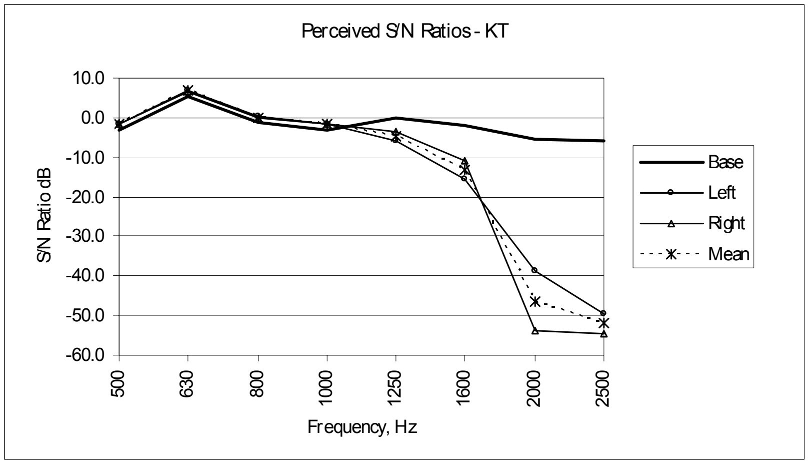


Adjusting the background noise and average word spectra for KT's audiometric results, as described above, lowered the overall background noise level by 1.5 dB and the overall speech level by 1.3 dB. The relatively small reductions reflect the dominant low to mid-frequency characteristics of both signals and KT's minor degree of hearing loss at these frequencies.

FIGURE 13:

Perceived signal-to-noise ratios for KT

Figure 13 shows S_f/N ratios for KT (left ear, right ear and average) and the perfect hearer, noting that the signal is speech and noise is the overall background level. A positive S_f/N means the speech component is louder than the background level.



It will be shown in later chapters that people can generally hear down to around 10 dB below the background level with speech discrimination ability significantly reduced when S/N becomes less than -5 dB. The above results suggest that KT should be able to discern all frequencies up to 1000 Hz as well as a person with no hearing loss. His speech discrimination ability should be affected by his high frequency hearing loss, meaning that consonant sounds should become harder to hear.

Test results

In order to classify the written responses to called words, three 'discrimination categories' were proposed, as follows:

- C1 = correct word
- C2 = C1 plus words with either the beginning or end sound correct, eg answered "COOL" for "TOOL".
- C3 = C1 & C2 plus words with neither the beginning nor end sound correct but correct vowel, eg answered "CART" for "PATH".

All three categories indicate that the called word was heard and not simply guessed. Table 3 presents a summary of caller/listener positions, S/N ratios and background noise levels at the listener positions for each of the seven tests, arranged in order of decreasing background level. The caller faced the listeners for all tests, and the listeners either faced the caller or had their backs turned.

TABLE 3:

Measurement parameters for first

Word list	Distance from source		Listener orientation	Average S/N ratio, dB		Background Level, dB(A)
	Caller	Listeners		500 – 1 kHz	1.6 – 4 kHZ	
List 1	5 m	0 m	Facing	-0.1	-8.9	85
List 7	0 m	10 m	Facing	-3.0	-6.4	82
List 3	40 m	20 m	Turned	-3.7	-10.6	81
List 2	20 m	10 m	Facing	2.4	-7.2	81
List 6	0 m	10 m	Facing	0.1	-6.8	78
List 4	30 m	20 m	Facing	0.1	-7.7	75
List 5*	30 m	20 m	Facing	>5	>5	35

** Noise source was turned off for this test.*

Figures 14 - 16 show speech discrimination scores in categories C1, C2 and C3 for each word list. Results averaged over all lists (except List 5) are shown in Figure 17.

FIGURE 14:

C1 discrimination

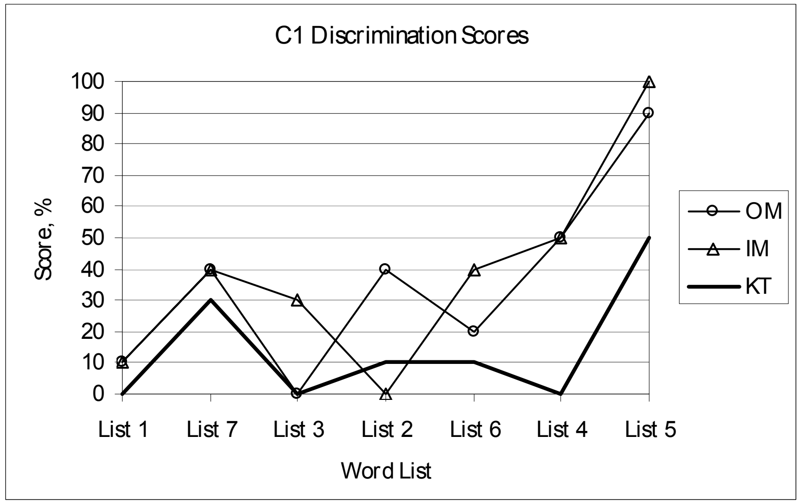


FIGURE 15:

C2 discrimination

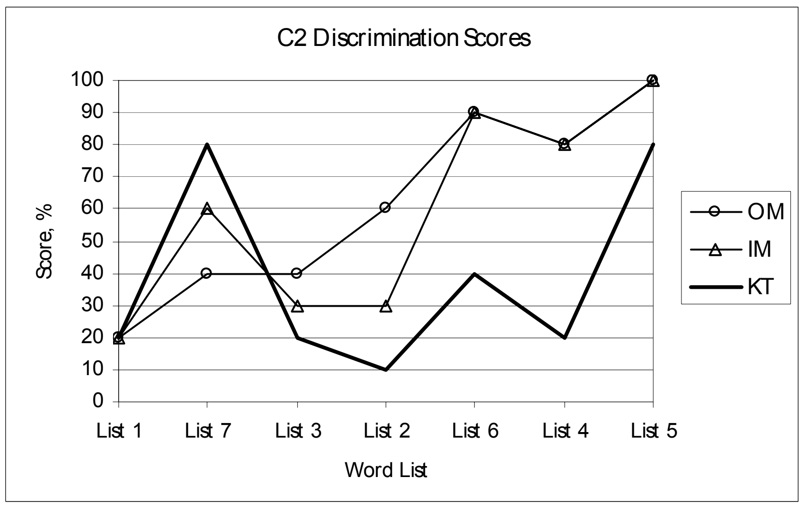


FIGURE 16:

C3 discrimination

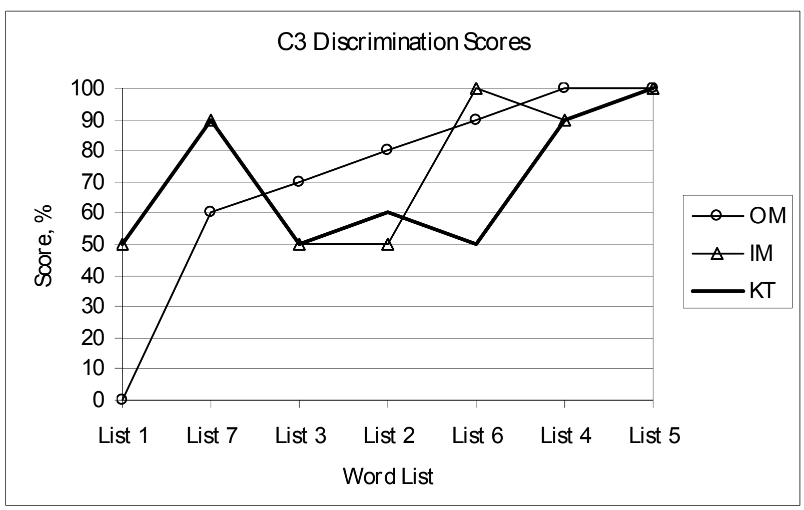
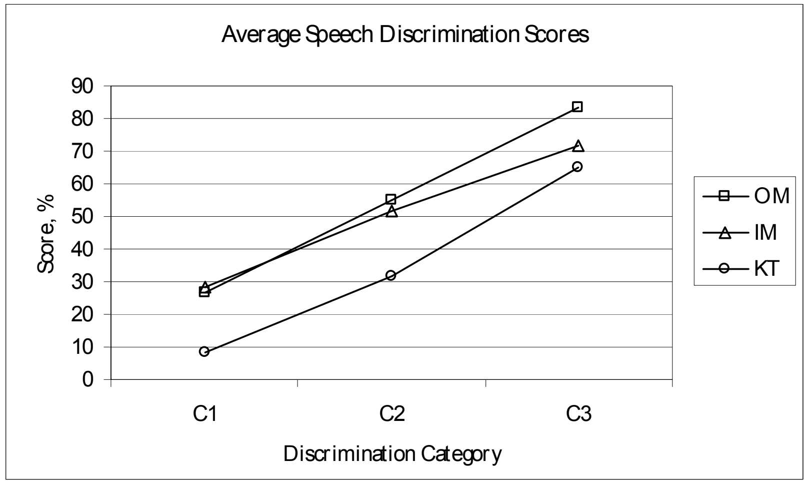


FIGURE 17:

Summary of discrimination scores



Discussion of results

The important features of the above results are discussed below.

- The test listeners OM and IM scored an average of 95 % in discrimination class C1 (exact word recorded) for word List 7 (no background noise). Test subject KT scored only 50 %, reflecting his reduced ability to hear speech in a quiet environment.

- Average C3 scores for OM and IM were 83 % and 72 % respectively, whereas KT scored an average of 66 % in this category. The high background levels appear to have had a greater detrimental effect on the consonant sounds than on the vowel sounds.

- KT scored very well across the categories on word List 7, which was called by the Author (Caller 2). As mentioned above, KT noted that Caller 1's voice was not particularly clear, whereas Caller 1 took particular care to enunciate the consonants in List 7. Without drawing too strong of a conclusion at this stage, it appears that the ability to hear a clear voice may be hampered more by high background noise levels than by high-frequency hearing loss. This is further evidenced by the generally poor scores for Lists 1 and 3, which were called by Caller 2.

- Discrimination scores for all listeners were generally lowest for Lists 1 and 3, which had high-frequency S/N ratios in the order of -10 dB.

- KT performed relatively poorly on Lists 6 and 4, which were called in the lowest background noise levels (apart from List 5). This suggests that high background noise levels tend to 'level the playing field' for impaired and non-impaired listeners, in terms of speech intelligibility.

Points for further consideration

As expected, the above results show that a person with NIHL has a diminished ability to discern shouted words. The important finding, however, is that high background levels have a greater impact on the speech discrimination abilities of the non-impaired listener than on the impaired listener, which tends to negate some of the NIHL sufferer's impairment.

Boothroyd words were specifically chosen for the initial tests described above because of the clear distinction between vowel and consonant sounds (and their correlation with certain frequency ranges) and also because of their lack of emotional content and familiarity. For a relevant practical test, words and phrases that may be used in an emergency situation were considered necessary, and a list of over 30 examples was compiled for use in future tests to refine the procedure.

The following points for further consideration arose from the initial tests:

- More NIHL sufferers need to be tested on Boothroyd words to give some statistical validity to the findings;

- Tests need to be conducted in a wider range of background noise levels to achieve a greater spread of S/N ratios.

- Listeners with NIHL spanning from slight to severe should to be included in the tests to help define an appropriate level of hearing loss (not necessarily 20 %) to trigger the need for further testing; and

- Meaningful words and phrases should be used in the final procedure and in its development.

Second underground test

Two other miners (AS and GP) who returned greater than 20 % binaural hearing loss were tested underground using four Boothroyd word lists and one list with meaningful words/phrases such as TELEVISION, FIRE and DON'T MOVE. The general procedure was the same as for the first test: the listeners included the two miners and a non-impaired control listener (SB). A caller was chosen from the workers' crew and instructed to call as loudly as he would in an emergency situation.

Preliminary findings

Figures 18 and 19 show the audiogram and PLH values for GP, whose total binaural hearing loss is 24.9%.

FIGURE 18:

Audiogram of subject GP in second test.

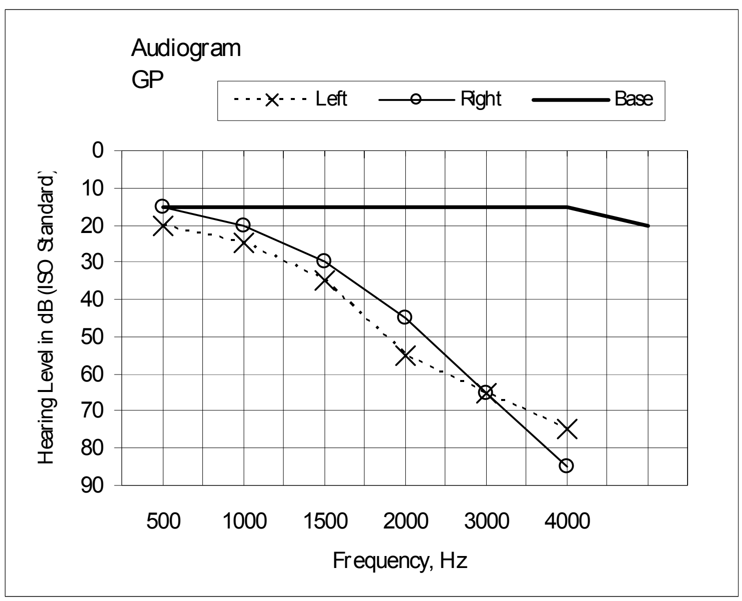
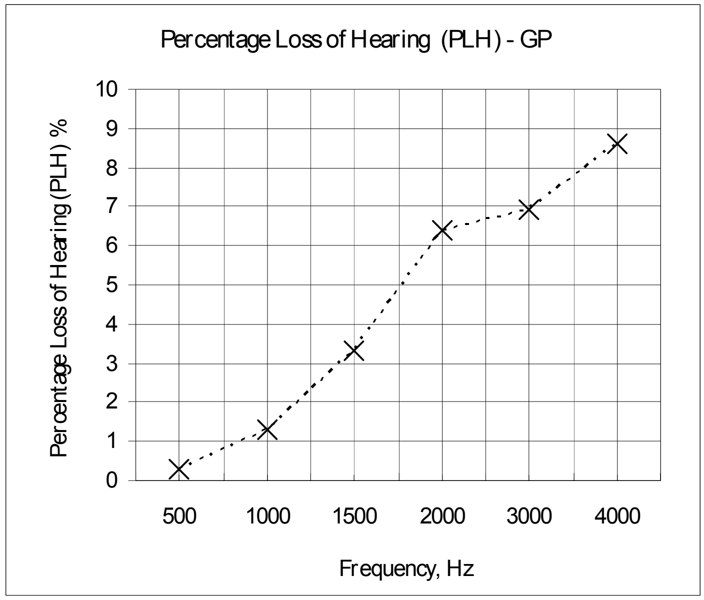


FIGURE 19:

Hearing loss of subject GP as a



These results show that GP has a relatively minor level of hearing loss (2 % PLH) at frequencies up to 1000 Hz (vowel frequencies and 'volume') and approximately 9 % PHL in the range 1500 HZ – 2000 Hz (consonants and speech clarity). The general nature of this hearing loss is similar to KT (see Figures 9 and 10) and similar test scores were expected.

Figures 20 and 21 show the audiogram and PLH values for AS, whose total binaural hearing loss is 36.8 %.

FIGURE 20:

Audiogram of subject AS in second test.

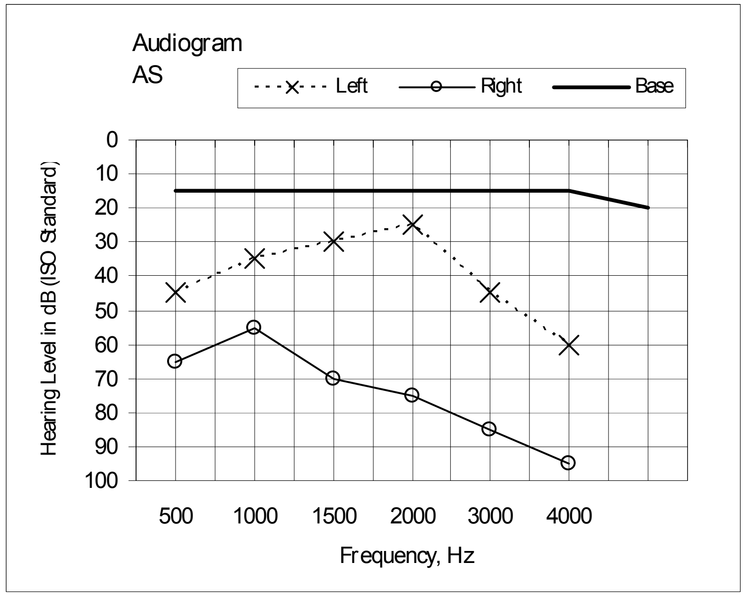
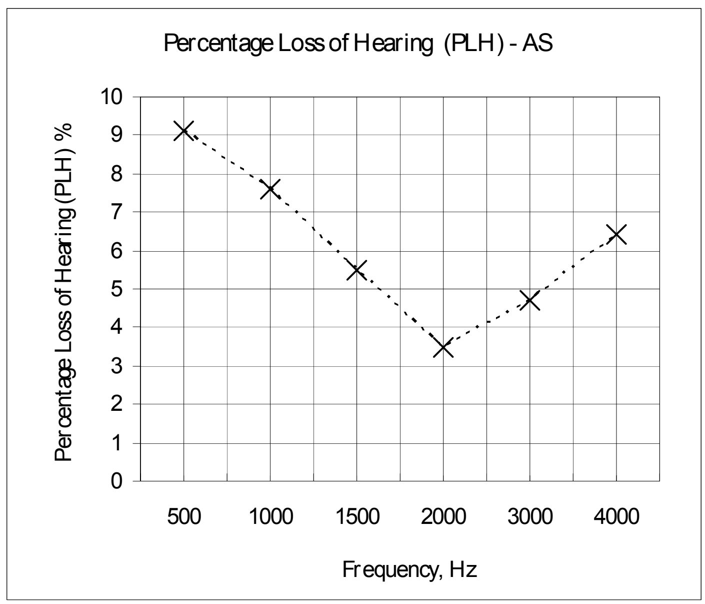


FIGURE 21:

Hearing loss of subject AS as a

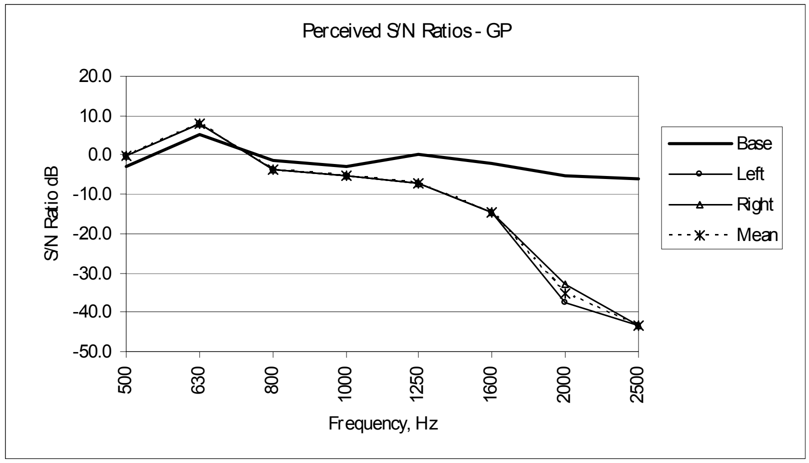


The nature of AS's hearing loss is significantly different to that of GP and KT and is not consistent with the typical pattern for NIHL. (It was revealed during the tests that AS's eardrums had been ruptured by an explosion over 30 years ago). Overall hearing loss is actually greater at low frequencies than at mid to high frequencies, with the right ear being much worse than the left.

Figure 22 shows the theoretical perceived S_f/N ratios for GP, calculated from the measured test results.

FIGURE 22:

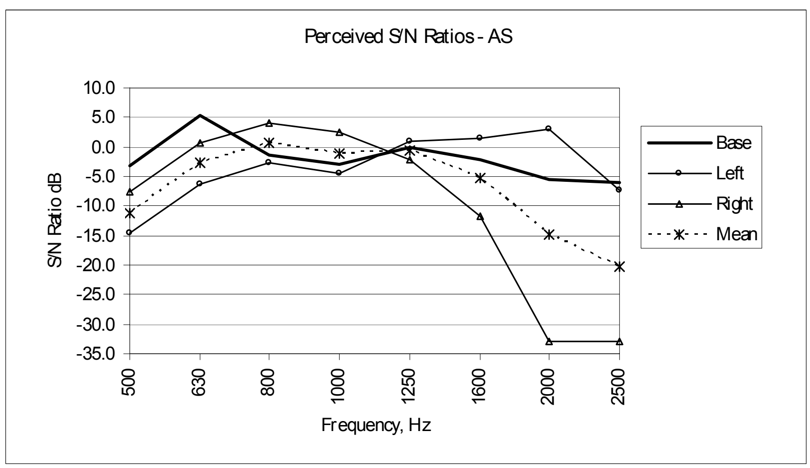
Theoretical perceived signal-to-noise ratios



The above curve suggests that GP should score poorly in the C1 and C2 discrimination categories, as his S_f/N values are less than -10 dB above 1500 Hz. Better C3 scores are anticipated due the minor hearing loss at low frequencies. Figure 23 shows the theoretical perceived S_f/N ratios for AS, again calculated from the measured test results.

FIGURE 23:

Theoretical perceived signal-to-noise ratios



These results, and the uncertain extent to which AP has adapted to his condition, make it difficult to predict test results.

Test results

Test scores over the three discrimination categories are shown in Figures 24-26 with averaged results shown in Figure 27.

FIGURE 24:

C1 discrimination scores in second test

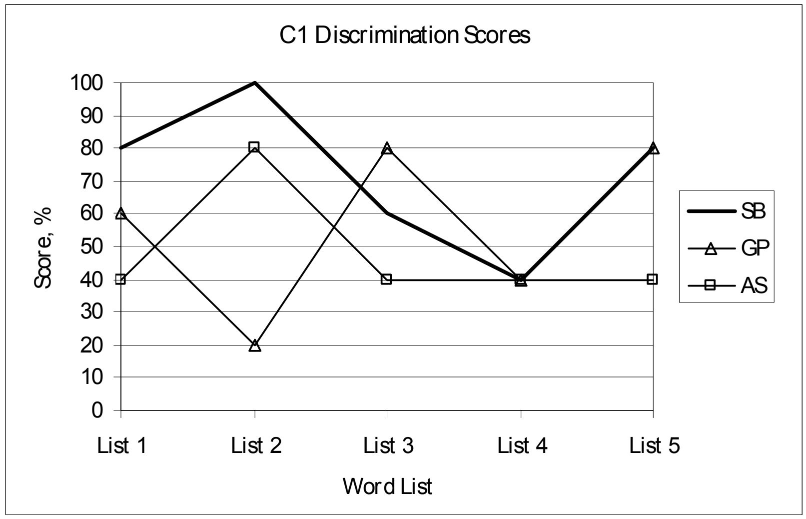


FIGURE 25:

C2 discrimination scores in second test

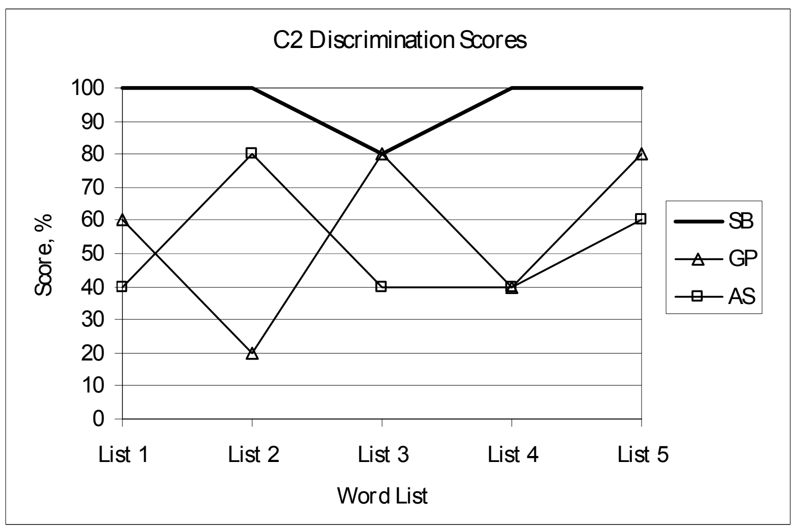


FIGURE 26:

C3 discrimination scores in second test

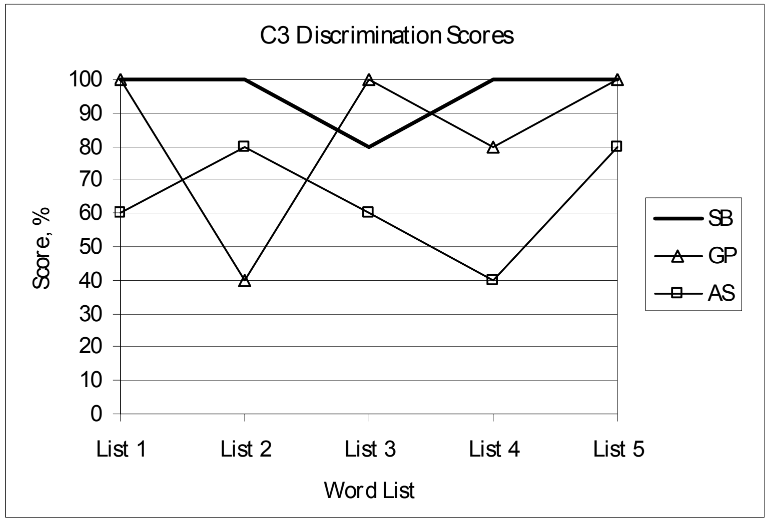
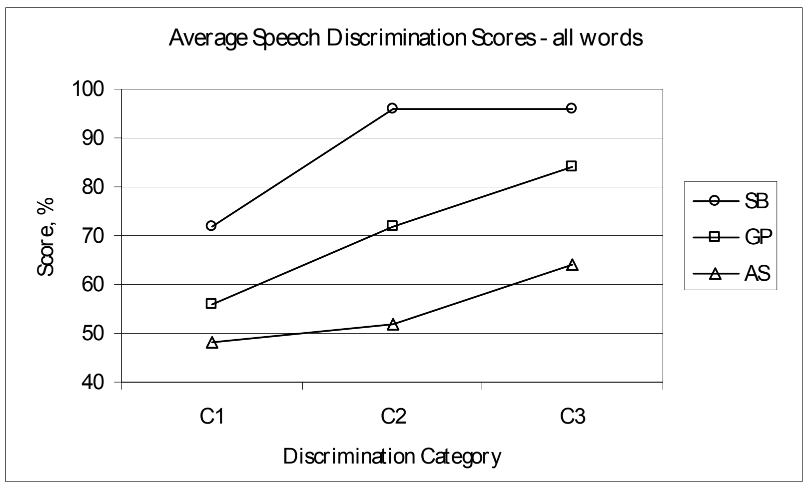


FIGURE 27:

Summary of discrimination scores



The most striking feature of these results is AS's C1 discrimination score of 80 % on List 2, which contained the meaningful words. Surprisingly, this was the poorest scoring list for GP, who scored very well on Lists 3 and 5. These two lists were called in the highest background noise levels. As discussed above, high background levels appear to have a greater relative impact on non-impaired listeners than those with NIHL.

This test again showed a narrowing of the C3 gap between a non-impaired listener and one with NIHL. Unfortunately, not enough emphasis was placed on meaningful words/phrases to test the significance of non-auditory cues.

Third underground test

When a fourth miner (MC) with binaural hearing loss greater than 20 % was identified, it was decided to conduct two separate tests: one using Boothroyd words (for comparison with earlier results) and one using words and phrases that would be familiar to the test subject, in the context of an underground emergency. Phrases such as WHERE'S THE DEPUTY, GET DOWN and EVERYBODY OUT were included, as were some phrases containing the subject's name.

It was believed that, not only being realistic, these phrases would contain some familiarity of expression that would lead to them being interpreted correctly even if they were not 'heard' completely. For example, it is highly likely that a hearing impaired listener would interpreted GET as BET or DOWN as SOUND. The phrase GET DOWN, however, is likely to be interpreted correctly, even if neither word sounded clear. When certain consonants are missing from a phrase, non-auditory faculties come into play to 'fill in the gaps' so that the message can be received correctly.

A PJB personnel carrier was used as a source of background noise. MC and a non-impaired control listener (RH) first stood at 10m from the PJB, with their backs turned to eliminate visual clues, and the caller stood on the back of the PJB. One list of ten Boothroyd words and one list of 10 phrases was called out. Caller and listeners then exchanged places for two more word lists (one Boothroyd and one meaningful).

Preliminary findings

Figures 28 and 29 show the audiogram and PLH values for MC, whose total binaural hearing loss is 25.6 %.

FIGURE 28:

Audiogram of subject MC in third test.

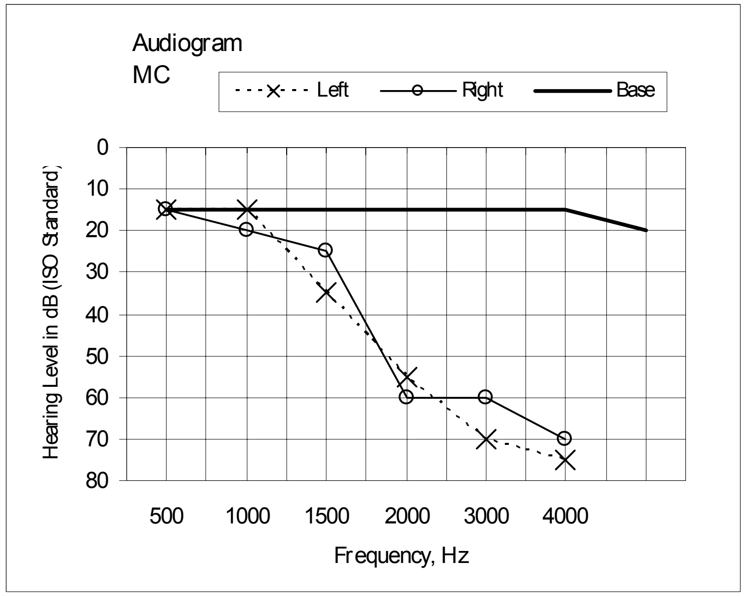
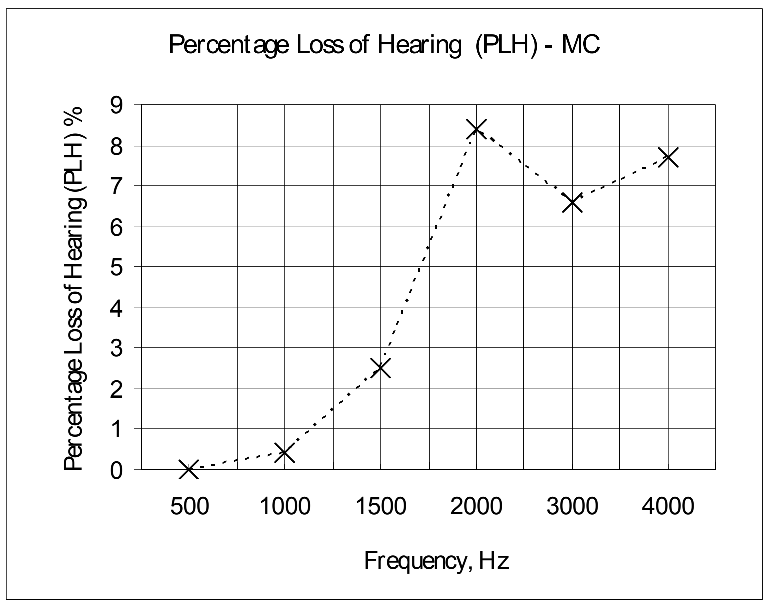


FIGURE 29:

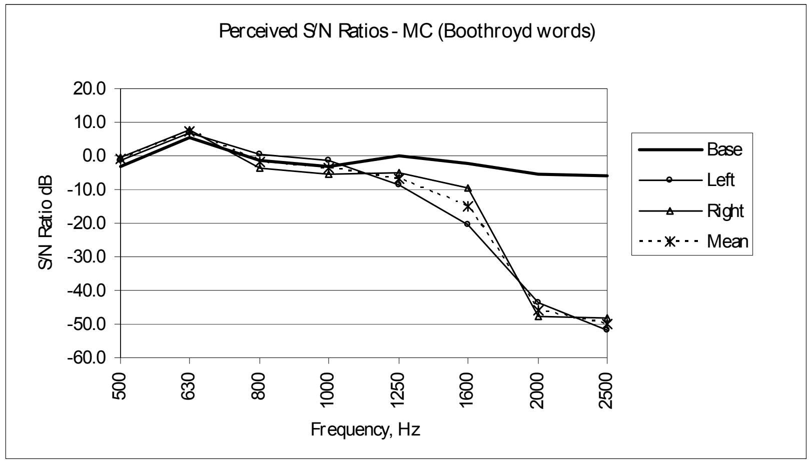
Hearing loss of subject MC as a



As with other audiometric curves typical of NIHL, most of MC's hearing loss (14 % PLH) is at frequencies above 2500 Hz. Theoretical perceived S_f/N curves are shown in Figure 30 for Boothroyd words only, based on measured results.

FIGURE 30:

Theoretical perceived signal-to-noise ratios for MC (Boothroyd

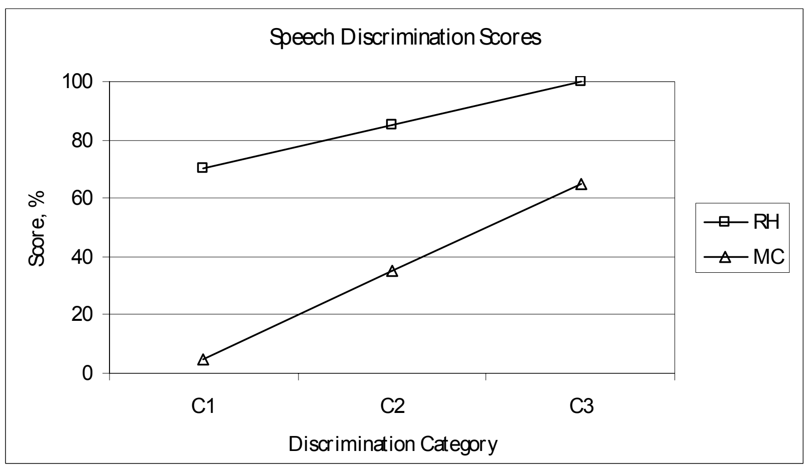


Test results

Figure 31 shows scores for two lists of Boothroyd words (20 words in total).

FIGURE 31:

Boothroyd word discrimination scores

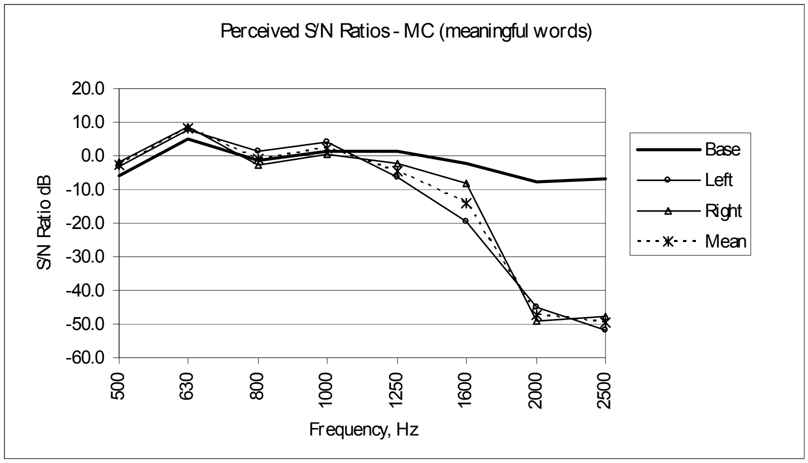


As expected, MC performed poorly on C1 scores, which reflect the ability to hear consonant sounds clearly. His ability to hear vowel sounds and the general 'form' of words was much greater, scoring 65 % on C3. It must be noted that after missing the first word MC seemed to become dejected and offered no answer to 35% of the words. Of the 65% answered, all scored at least C3.

The results were quite different for the meaningful phrases. MC scored 100 % correct (discrimination categories C1 – C3 are not defined for multi-syllable words) whereas RH scored only 95 %. Figure 32 shows S_f/N ratios for the twenty meaningful words, as measured at MC's ear.

FIGURE 32:

Theoretical perceived signal-to-noise ratios for MC (meaningful



Discussion of results

The similarities between Figures 29 and 31 reflect the consistency of spectral composition of Boothroyd and meaningful words. When presented on a graph, both types of words appear almost identical. In the practical hearing tests, however, familiarity and other auditory cues combine to produce much higher test scores for the meaningful words.

Other research findings

The main focus of the current work is to determine critical perceived S/N ratios at which a raised voice may be heard by a person with significant NIHL 'almost as well as' a person with little or no hearing loss, in an environment of constant high background noise. Unfortunately, most published material on speech intelligibility is concerned with the internal acoustics of speech auditoria, where background noise levels are not very high and the test listeners do not have a high degree of hearing loss. Studies on people with greater than 20 % hearing loss are often geared towards finding better hearing protection or hearing aids.

Several research papers relevant to the present study were found and investigated. Those that were able to contribute to this study are summarized below.

Sato (1994)

An experiment was conducted by Sato et. al. [6] to observe the differences between speech discrimination abilities of normal hearing (Group A) and hearing impaired (Group B) listeners. The ultimate goal of the study was to optimise established Articulation Index (AI) parameters for both groups of listeners.

The experiment involved presenting the two groups of listeners with vowel or vowel-consonant words under S/N conditions of -25, -20, -15, -10 and 0 dB. (These words are similar to the Boothroyd words used in experiments described earlier and generally poor results are expected for the higher S/N ratios).

Background noise was presented at centre frequencies of 500, 1000, 2000 and 4000 Hz, one band at a time. Sato's S/N was taken as the overall signal level versus background noise in a specific frequency band, whereas the present study defines S/N as the signal level in each third-octave band versus the overall broad-band background level.

Sato's experimental results (averages only) for Groups A and B are summarized in Table 4 below. Error margins generally increased for decreasing S/N with more variation in Group B than Group A.
The column labeled 'Ratio B/A' has been inserted to show the performance of Group B relative to Group A. It is these values that will be relevant in the present study.

Table 4:

Summary of test results from

Noise @ 500 Hz	Score (% correct)		
S/N Ratio	Group A	Group B	Ratio B/A (%)
-25	51	20	39.2
-20	62	33	53.2
-15	94	53	56.4
-10	97	75	77.3
0	99	89	89.9
Noise @ 1000 Hz	Score (% correct)		
S/N Ratio	Group A	Group B	Ratio B/A (%)
-25	38	17	44.7
-20	54	28	51.9
-15	83	50	60.2
-10	92	68	73.9
0	97	88	90.7
Noise @ 2000 Hz	Score (% correct)		
S/N Ratio	Group A	Group B	Ratio B/A (%)
-25	41	24	58.5
-20	52	27	51.9
-15	63	40	63.5
-10	74	51	68.9
0	82	72	87.8
Noise @ 4000 Hz	Score (% correct)		
S/N Ratio	Group A	Group B	Ratio B/A (%)
-25	43	32	74.4
-20	52	40	76.9

-15	62	52	83.9
-10	77	62	80.5
0	86	78	90.7

Figure 33 shows Sato's results for impaired and non-impaired listeners, averaged over the four octave bands covering 500 Hz – 4000 Hz.

FIGURE 33:

Test scores vs signal-to-noise ratio (from

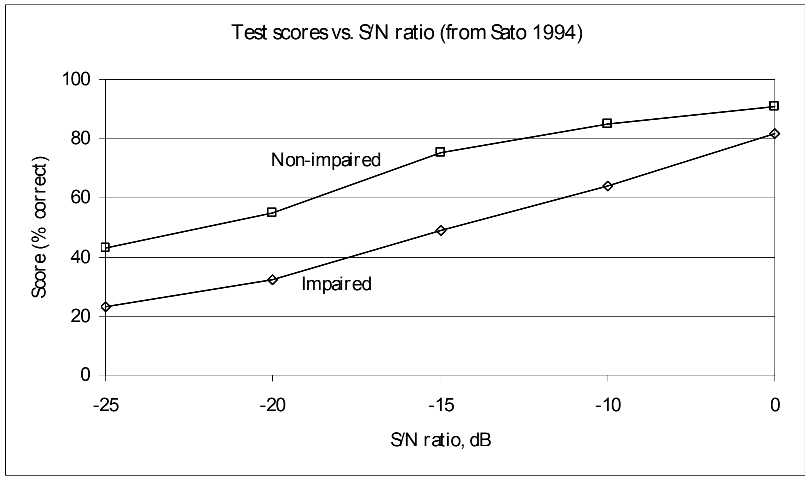
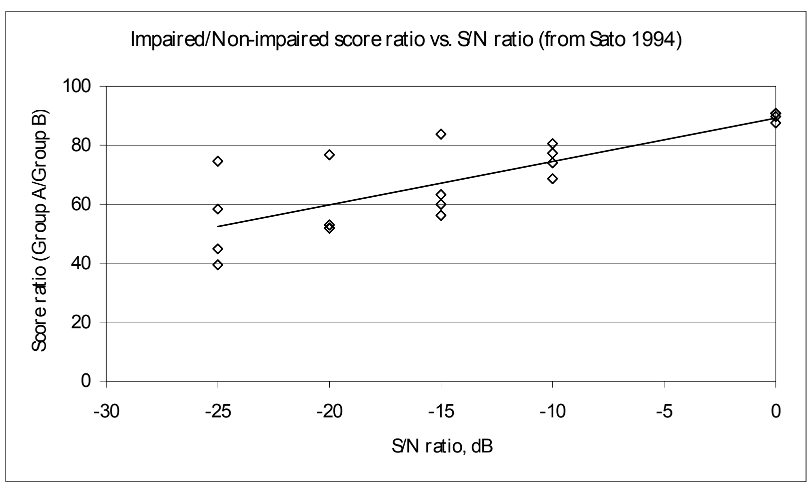


Figure 34 shows the B/A ratios from the above data and a best-fit regression line. The line represents the test score relativities averaged over the four octave bands.

FIGURE 34:

Relationship between impaired and non-impaired listeners' scores (from Sato.



The regression line in Figure 33 has equation

$$\text{Score ratio} = 1.5\,(S/N) + 89.3 \qquad (1)$$

with correlation coefficient r = 0.8. Equation 1 predicts that the hearing impaired group performs 82 % as well as the non-impaired listeners at a S/N ratio of -5 dB. The two groups should perform equally when S/N is +7 dB.

Reference to the perceived S_f/N curves for three workers with typical NIHL audiometric results (Figures 9, 18 and 28) suggests that vowels (800 Hz) were typically presented at an S/N ratio of 0 dB, with S/N being around -10 dB for consonants (1600 Hz). Substituting these S/N values into Equation 1 gives projected score ratios of 89 % and 74 %, respectively.

The implication for the present study is that vowel sounds should be heard by impaired listeners 89 % as well as they are heard by non-impaired listeners, while consonant sounds should only be heard about 74 % as well. S/N = 0 can be taken to reflect C3 scores (the vowels were definitely heard) and S/N = -10 to reflect C2 scores (since the words in Sato's test were at most mono-consonant).

Table 5 shows a summary of C2 and C3 scores for KT and GP[1] (as a ratio with test scores for non-impaired listeners), their averages and the interpolated results of Sato.

Table 5:

Comparison between test results and those

Category	KT	GP	Average	Sato
C3	79.2	86.6	83	89
C2	61.5	74.2	68	74

The above comparison with Sato's results suggests the following:

- S/N ratio is a strong determinant of speech intelligibility for both impaired and non-impaired listeners;
- The average (relative) performance of KT and GP was 6% lower than for Sato's listeners and was most probably due to their higher degree of hearing loss; and

[1] Test results for MC are not included as not enough test words were used for statistical reliability.

- It should be possible to determine a relationship between background noise level and S/N ratio for meaningful phrases in the underground environment. An acceptable level of reduced hearing performance could then be equated to a critical S/N ratio.

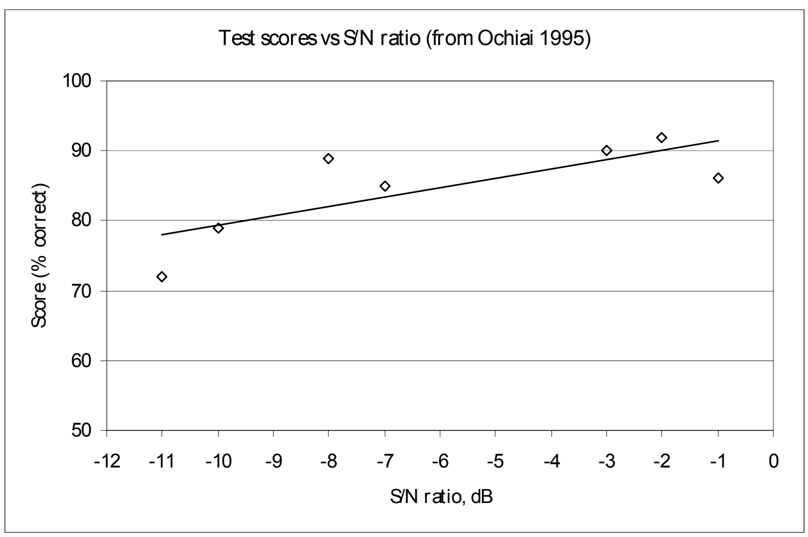
The last point above will be used in defining a critical hearing loss spectrum that will trigger the need for a practical underground hearing test.

Ochiai (1995)

A group of Japanese researchers investigated the effect of various noise environments on speech intelligibility [7]. The subjective experiment involved monosyllable words being presented to ten test subjects against seven different types of background noise at several S/N ratios. Seven of the ten subjects had no hearing impairment, while the remaining two had mild sensorineural hearing loss. Figure 35 shows test scores for the non-impaired listeners.

FIGURE 35:

Test scores for non-impaired listeners (from Ochiai, 1995)



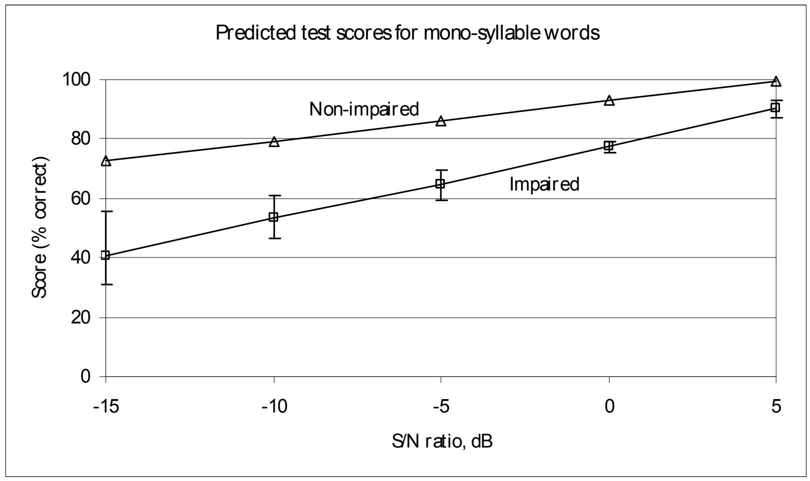
These results are very similar to Sato's findings for non-impaired listeners (see Figure 34). Applying the corrections for impaired listeners from the regression line in Figure 35, plus an extra 6 % as determined from this study, gives the line shown in Figure 36, with equation

$$\text{Score} = 2.6(S/N) + 77.4 \qquad (2)$$

This curve/equation may be used to predict scores for mono-syllable word tests conducted in the underground environment, for listeners with NIHL typified by the audiometric curves of KT and GP (shown in Figures 9 and 18).

FIGURE 36:

Test score prediction curve for non-impaired and impaired listeners, appropriate for high-level NIHL and typical



Bradley (1999)

A recent study conducted by Bradley et. al. [8] sought to investigate the importance of both S/N ratio and room acoustics on speech intelligibility. This paper is widely referenced by investigators working in architectural acoustics. The experiment involved calling mono-syllable words to non-impaired test subjects in a room where both the S/N ratio and reverberation times were varied.

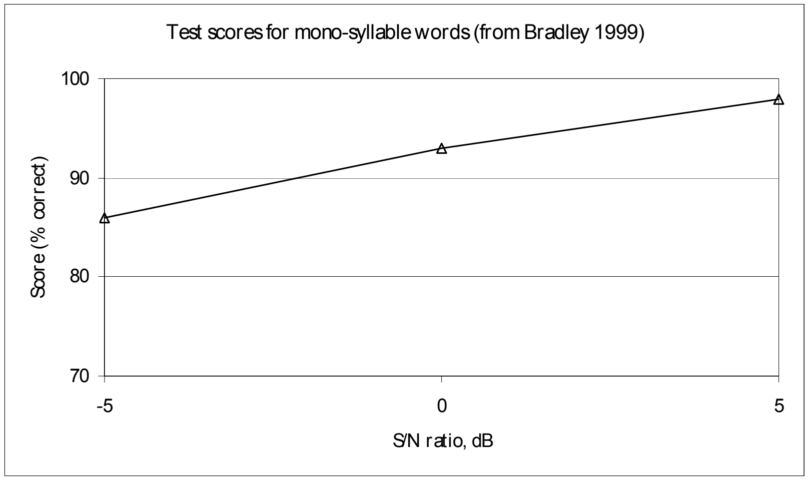
Bradley found S/N ratio to be a much greater determinant of test results than reverberation time, with virtually identical results for reverberation times of 0.5s and 1s. Figure 37 shows Bradley's results for a reverberation time of 1s.

The best-fit line to the data points in Figure 37 has equation

$$\text{Score} = 1.2(S/N) + 92 \qquad (3)$$

FIGURE 37:

Test results for monosyllable words called to non-impaired listeners in an environment acoustically similar to the underground



Points for further consideration

It has been found in studies conducted for this project, and others discussed above, that decreasing S/N ratios (effectively, increasing levels of background noise) significantly affect the NIHL sufferer's ability to distinguish words used in standard speech intelligibility (SI) tests.

If such tests were the benchmark for assessing the safety implications of miners with moderate – severe NIHL, then it is unlikely that these workers could be deemed safe. Their test scores in the typical underground noise environment (-5<S/N<5 dB) is approximately 20-30 % less than their non-impaired counterparts, scoring only 50 % correct (ie, C1/C2) and 75 % 'vowel-correct' (ie, C3). The ability to hear only 50-75 % of words correctly may not be considered adequate for safety purposes.

Note that all previous discussions have been concerned with standard SI testing. Such tests are not relevant to the issue at hand in which workers are required to hear shouted warning words/phrases adequately. Following is a summary of the essential points to consider in devising the practical test:

- Meaningful words/phrases must be used;

- The tests should be conducted underground or in a simulated underground environment (no light or listener facing away from caller);
- Overall S/N during the test should be in the range -10 – +5 dB;
- Background levels should be in the range 75 – 90 dB(A);
- At least 20 words/phrases should be used for statistical validity;
- A control (non-impaired or minimally impaired) listener should be included in the test for comparative purposes; and
- The worker being tested should score more than 80% of the overall test score of the control listener.

Final field study

The preceding Chapters have revealed the required basic elements of the testing procedure, and found that standard speech intelligibility tests are not appropriate. Before detailing the proposed test procedure, however, it remains to determine the level of hearing loss (as revealed in an audiometric examination) that will trigger the need for a practical test.

Test environment

A reasonably large and reverberant hall was chosen for the test. Digitally generated pink (broadband) noise was played on a Digital Audio Tape (DAT) recorder through a 400W power speaker. The speaker was of sufficient power to reproduce the pink noise without distortion over the entire assessed frequency range.

The speakers were placed at the rear of the hall, directed into the corners so that the reflected sound produced a relatively uniform acoustic field. A Svan 912 third-octave band sound level meter (IEC Type 1) was used to measure the background noise level at the listeners' desk, which was located near the centre of the hall.

A caller (the Author) stood at a spot near the front of the hall and called out words/phrases is the absence of background noise and the average (Leq) level was measured at the listeners' desk. Once it was established that the caller's voice measured 80 dB(A) at the desk, the words were called once again with the same vocal effort and measured at a distance of 1 m, registering 88 dB(A). The purpose of this was so that, when the test was under way, the caller could look at the noise meter 1 m away and be sure that a consistent signal of 80 dB(A) was received at the listeners' desk.

During the test, the volume of pink noise was adjusted on the speaker to achieve S/N ratios of -10, -5, 0 and +5 dB(A) at the listeners' desk. For a speech level of 80 dB(A), the corresponding background noise levels were 75, 80, 85 and 90 dB(A). Ten mono-syllable words and ten meaningful words/phrases were called at each S/N level with time given for responses to be recorded.

Test listeners

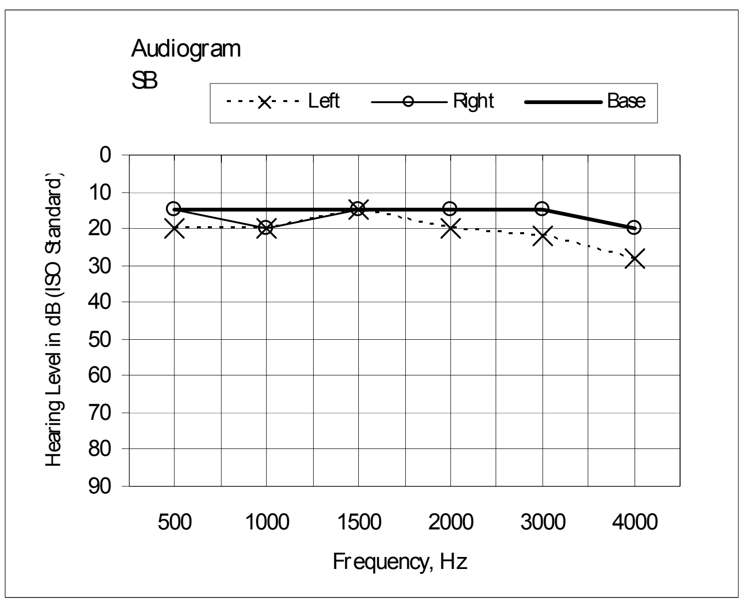
Three listeners with binaural hearing losses as follows participated in the test:

SB: Male, age 38, binaural hearing loss 1.6 %,
GT: Male, age 54, binaural hearing loss 15.5 % and
DB: Male, age 57, binaural hearing loss 43.7 %.

These listeners have NIHL ranging from virtually nil to very severe, an ideal spread for this test. Their audiometric results are shown in Figures 38 to 43. A summary of PLH for the various frequency ranges is also given for each listener.

FIGURE 38:

Audiogram for test listener SB. Total binaural hearing loss



Frequency range, Hz	Threshold level, dB	Severity of Hearing Loss	PLH, %	Speech component
400 - 800	15	No significant loss	0.5	Vowels
800 - 1500	15 -20	No significant loss	1	None
1500 - 2500	15 -20	No significant loss	0.1	Consonants
> 2500	15-30	No significant loss	0	None

FIGURE 39:

Percentage loss of hearing for test listener SB as a

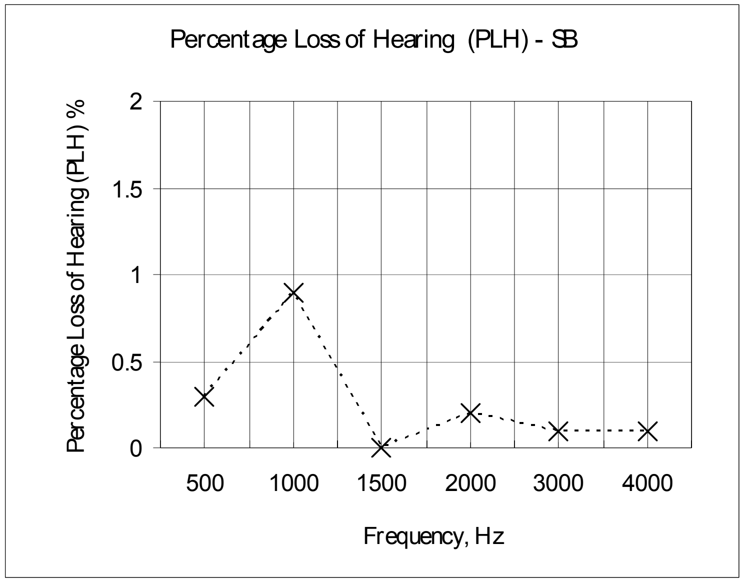
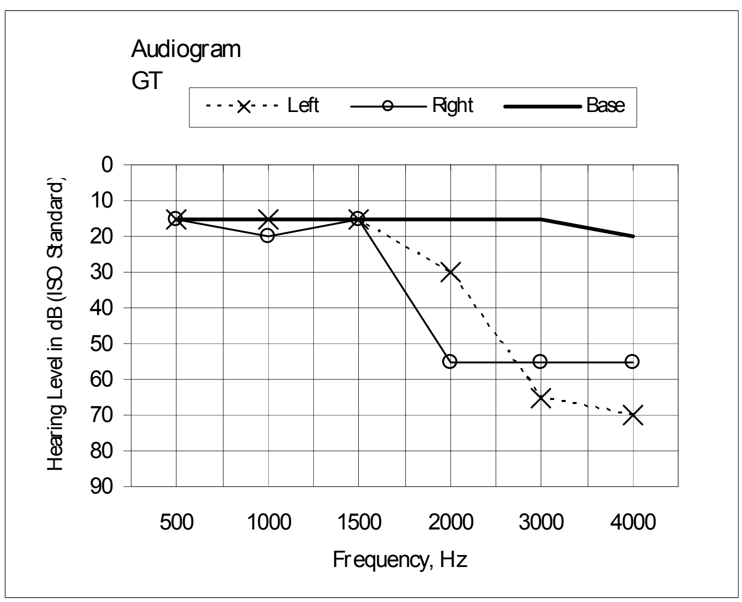


FIGURE 40:

Audiogram for test listener GT. Total binaural hearing loss



Frequency range, Hz	Threshold level, dB	Severity of Hearing Loss	PLH, %	Speech component
400 - 800	15	No loss	0	Vowels
800 - 1500	15 - 20	Nil – Slight	0.5	None
1500 - 2500	30 - 60	Mild – moderately severe	5	Consonants
> 2500	60 - 70	Moderately severe	10	None

FIGURE 41:

Percentage loss of hearing for test listener GT as a

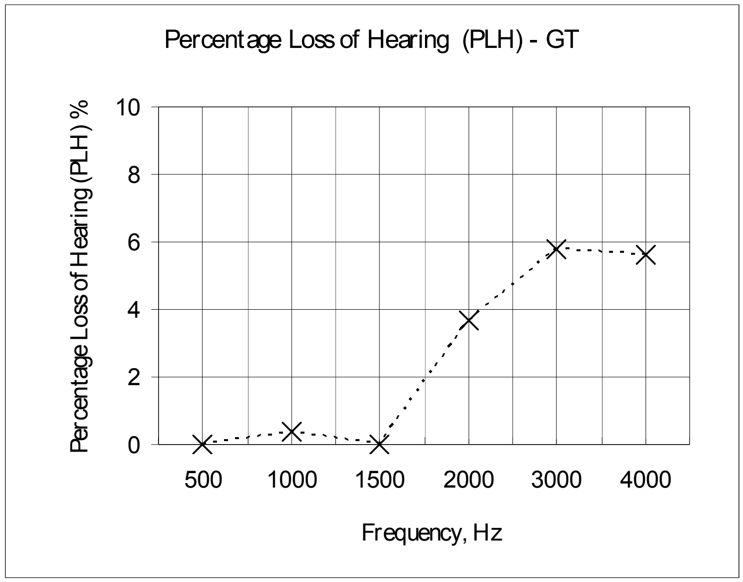
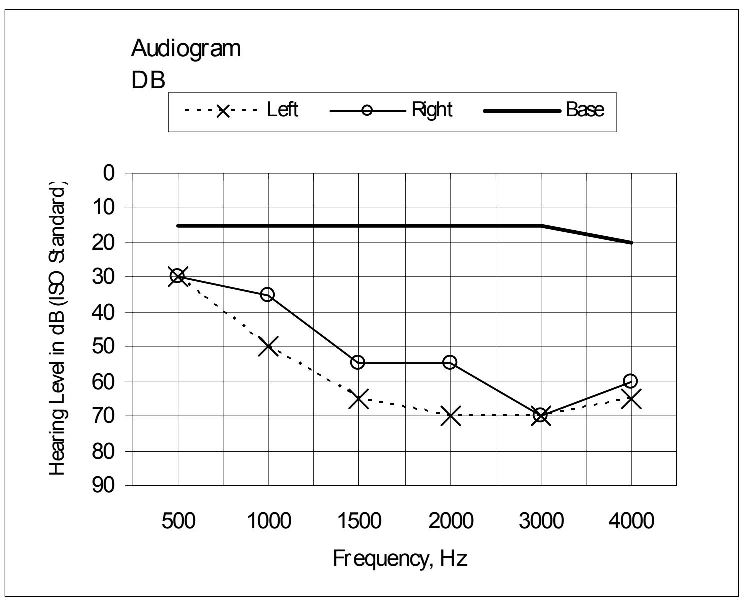


FIGURE 42:

Audiogram for test listener DB. Total binaural hearing loss

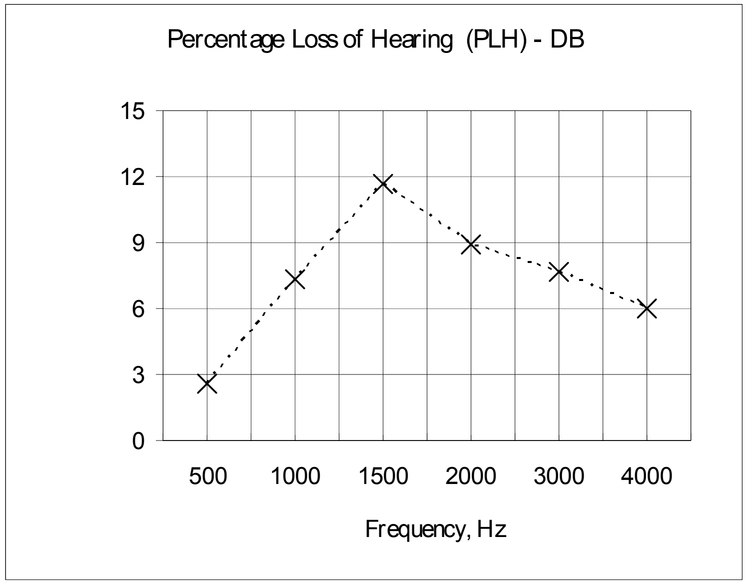


Frequency	Threshold			Speech

range, Hz	level, dB	Severity of Hearing Loss	PLH, %	component
400 - 800	15 - 40	Slight – mild	3	Vowels
800 - 1500	30 - 65	Mild – moderately severe	16.7	None
1500 - 2500	65 - 75	Moderately severe – severe	10	Consonants
> 2500	65 - 75	Moderately severe – severe	14	None

FIGURE 43:

Percentage loss of hearing for test listener DB as a



Intermediate results

The following Figures 44 to 46 show perceived S_f/N ratios for the three test listeners, standardized to an overall S/N ratio of 0 dB as measured on the sound level meter.

FIGURE 44:

Perceived S/N ratios for test listener SB.

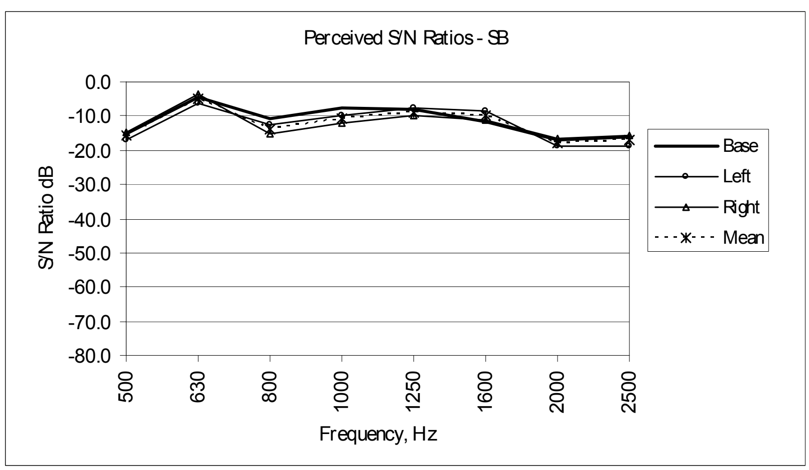


FIGURE 45:

Perceived S/N ratios for test listener GT.

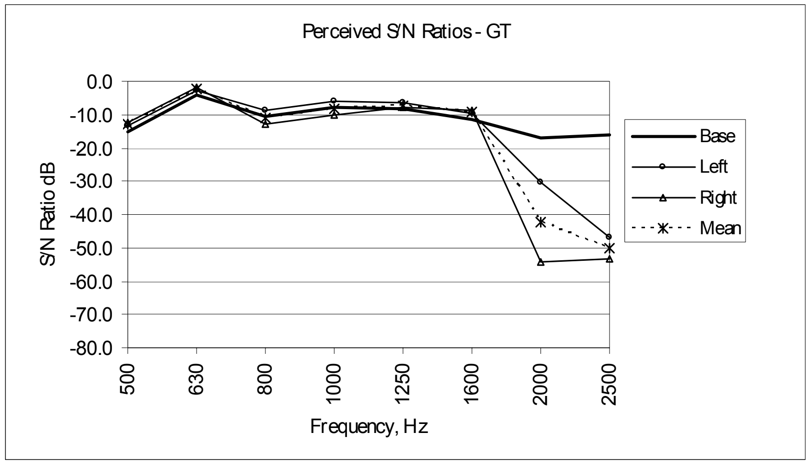
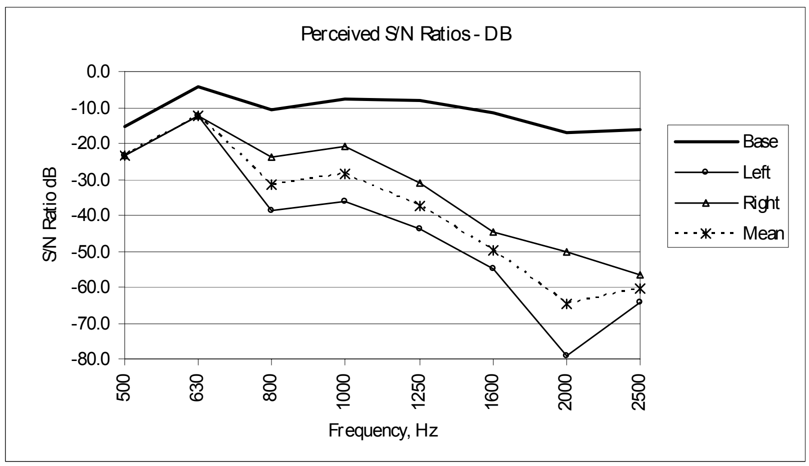


FIGURE 46:

Perceived S/N ratios for test listener DB.



Comparing Figures 44 and 45, it is evident that GT should hear vowel sounds as well as SB at S/N = 0 dB. His ability to hear consonants diminishes greatly for frequencies above 1600 Hz, so his C1 scores are expected to be low.

Figure 46 shows that even at S/N = 0 (which means that the overall speech level is equal to the background level) DB perceives vowel sounds at approximately 12 dB below the background level and consonants at more than 40 dB below the background level. His score is expected to be extremely low in all discrimination categories for Boothroyd words. Both GT and DB are expected to perform better on the meaningful phrases than the above Figures would indicate.

Test results

Boothroyd words

Figures 47 to 50 show speech discrimination scores for the three listeners at overall S/N ratios of -10, -5, 0 and +5 dB.

FIGURE 47:

Speech discrimination scores for mono-syllable words with

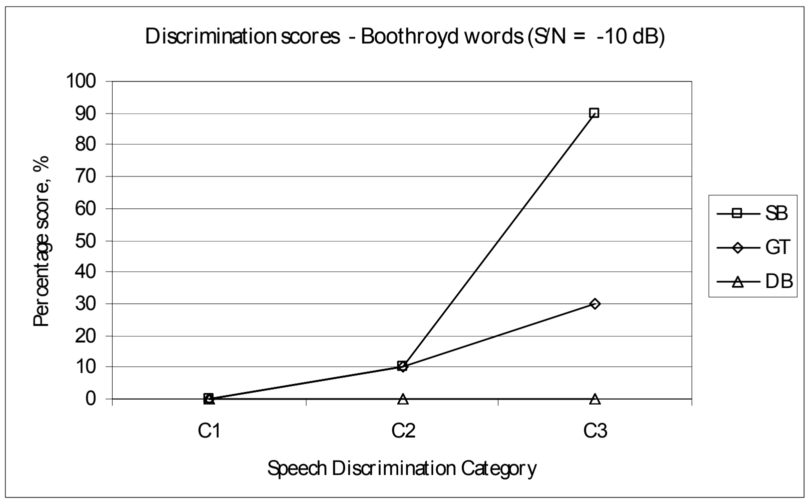


FIGURE 48:

Speech discrimination scores for mono-syllable words with

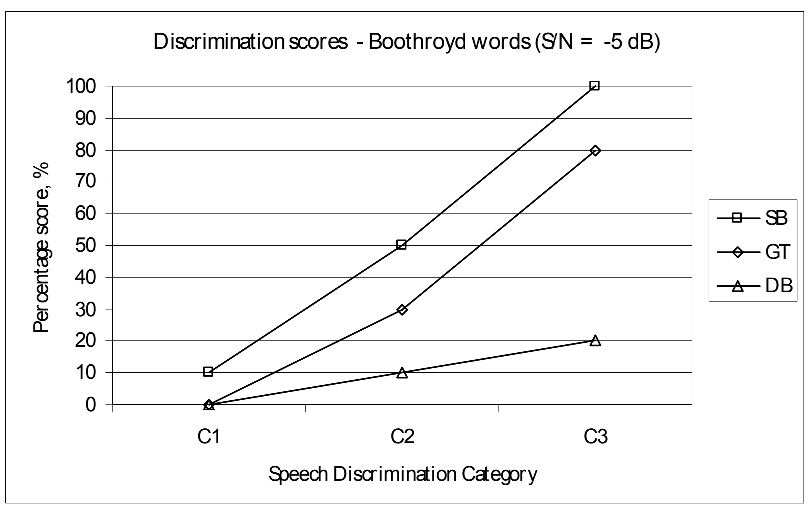


FIGURE 49:

Speech discrimination scores for mono-syllable words with

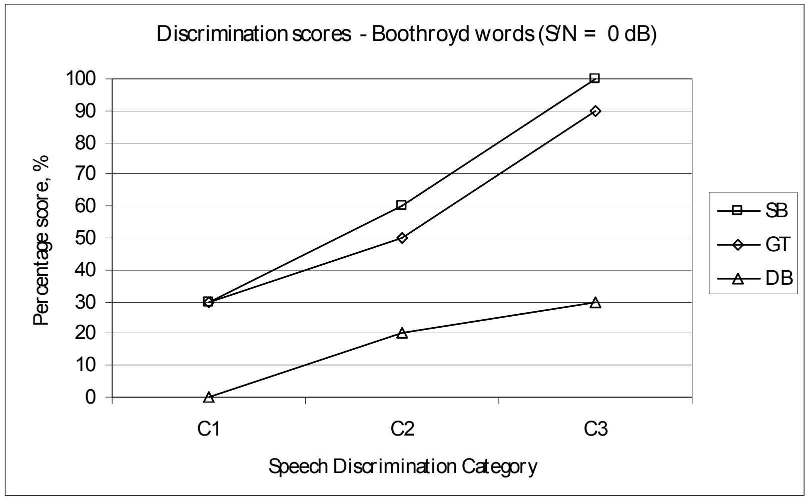
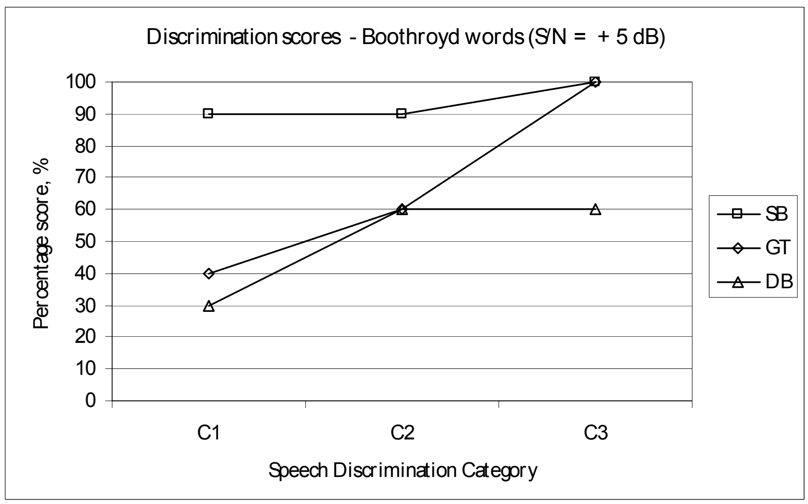


FIGURE 50:

Speech discrimination scores for mono-syllable words with

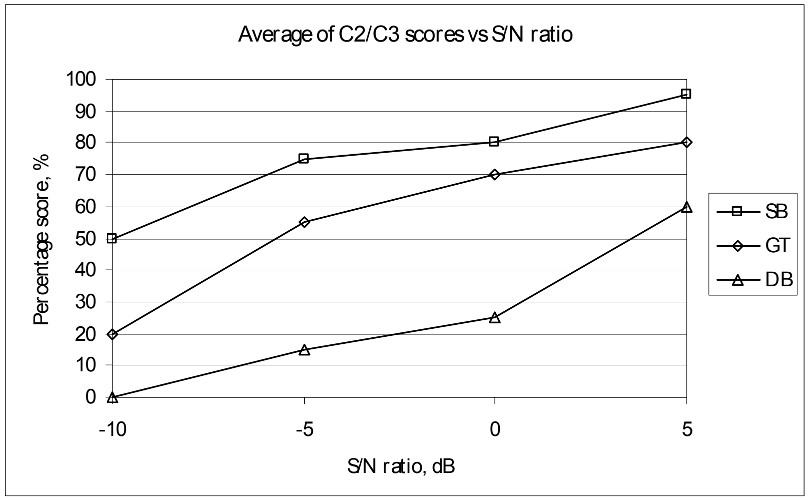


Previous results suggest that a person needs to be able to hear most vowel sounds and some consonants in order to correctly identify meaningful phrases. The missing information is "filled in" so that the whole phrase is identifiable even when individual words are not.

It is proposed that the average of C2 and C3 scores in single-word tests may indicate the likelihood of the listener being able to correctly interpret meaningful phrases. Figure 51 below summarises the average C2/C3 scores in Figures 47 – 50 as a function of overall S/N ratio.

FIGURE 51:

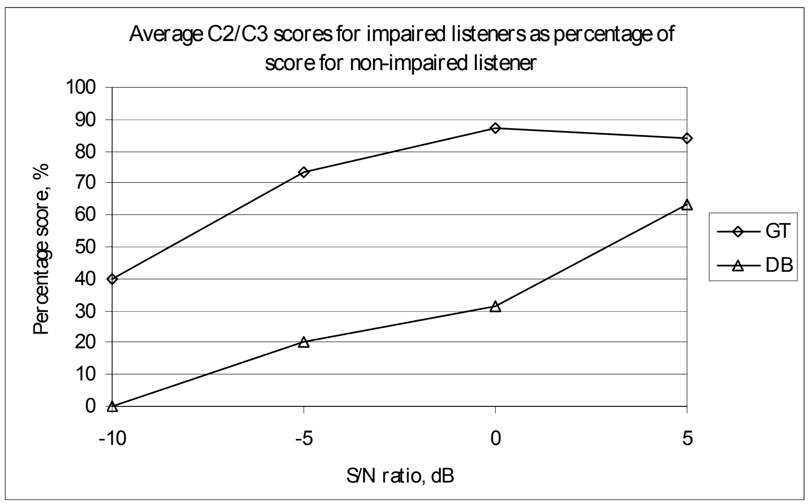
Summary of mono-syllable speech discrimination scores for the three tested



Finally, Figure 52 shows the above scores for GT and DB expressed as a percentage of the score for virtually unimpaired listener SB.

FIGURE 51:

Summary of mono-syllabel speech discrimination scores for impaired listeners as a percentage of the



Meaningful phrases

Test results for meaningful phrases are summarized in Figure 53. Results for impaired listeners as a percentage of the score for the non-impaired listener are shown in Figure 54.

FIGURE 53:

Summary of meaningful phrase discrimination scores for the three tested

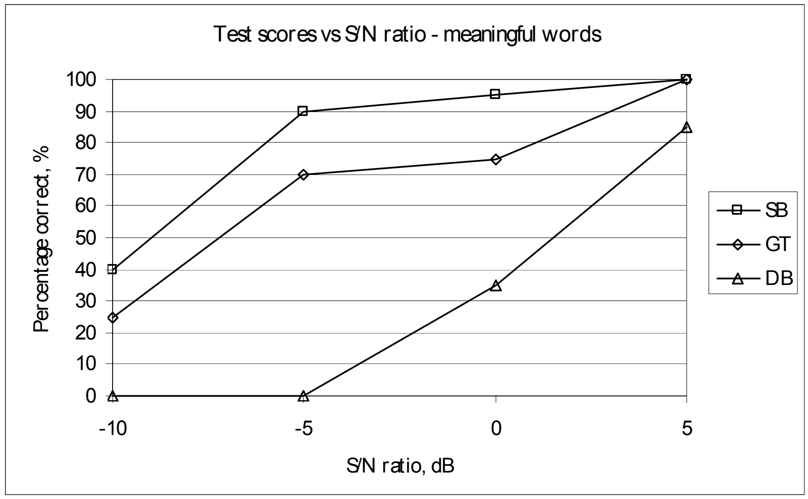
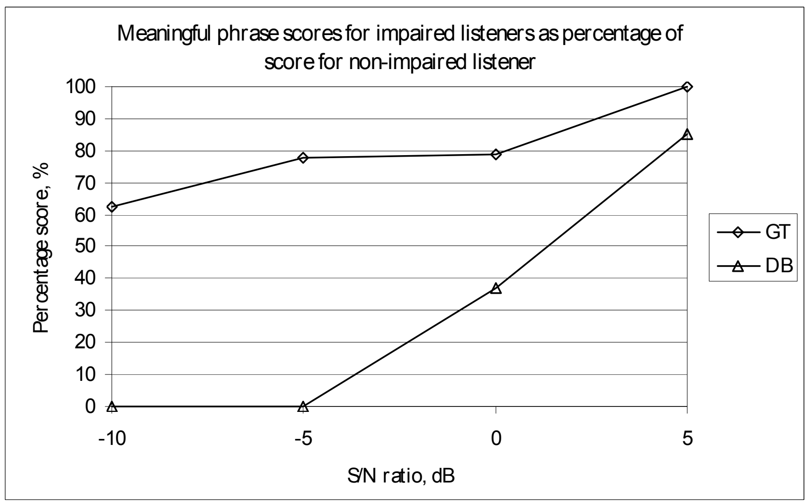


FIGURE 54:

Summary of meaningful phrase speech discrimination scores for impaired listeners as a percentage of the



Considering Figures 52 and 54, GT achieved an average of 81% of the score of an unimpaired listener over the S/N range -5 to +5 dB for mono-syllable words and 86% for meaningful phrases. Given the range of noise levels measured in the underground environment and the variability of sound output with vocal effort, shouted speech typically achieves positive S/N ratios when the caller is intent on being heard (see for example Figures 12 and 13).

The results for DB in Figures 52 and 54 suggest that his hearing ability is greatly hampered for S/N ratios less than about +5 dB. Even at S/N = 0 dB, he scored well under half of the score of an unimpaired listener. This person should probably be deemed unsafe in the underground environment.

Summary of findings

It has been found in this research program that people can have sustained quite high levels of NIHL before their ability to hear shouted instructions reduces to less than 80% of the hearing ability of an unimpaired listener. It is critical, however, that there are only very minor threshold shifts at frequencies below 1000 Hz.

Most sensorineural hearing loss begins with a threshold shift at 4000 Hz. As the "dip" increases with continued exposure to noise, frequencies below 4000 Hz begin to show threshold shifts also. When the frequencies from 1600 Hz to 2500 Hz are affected, the ability to hear consonant sounds is reduced. In the noisy underground environment, however, the impaired listener is able to "fill in" missing auditory details from individual words to identify meaningful phrases.

When the advancement of NIHL begins to produce threshold shifts at frequencies below 1000 Hz, the ability to hear vowel sounds is hampered and, of course, the ability to hear consonants is greatly affected due to the larger threshold shifts at higher frequencies.

It has also been found that for a non-impaired listener, test scores reduce to unacceptably low levels once the overall S/N ratio reduces to less than -5 dB. Such marked reduction in performance was not observed by other researchers dealing with much lower overall noise levels and people with <10 % binaural hearing loss.

Critical audiogram to trigger practical test

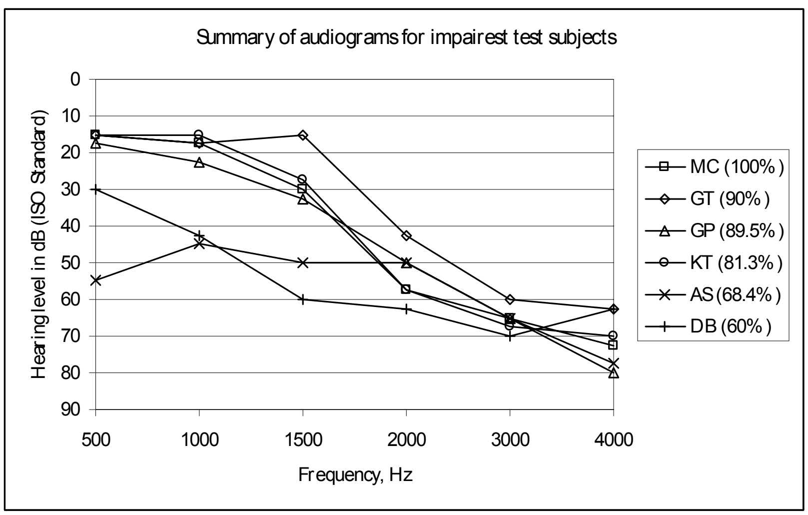
It was found in the first underground test that listener KT performed to around 80% of the C3 discrimination score (Boothroyd words) of an unimpaired listener in an environment where S/N = +5 dB. Subsequent tests suggested that a higher proportion of meaningful phrases would have been heard correctly. Similarly, MC had a high degree of typical NIHL, yet he scored 100% of meaningful phrases correct in an S/N = +5 dB environment. A third person tested (GT) also scored very well in S/N environments ranging from -5 to +5 dB. It is proposed that these individuals can hear well enough for safety purposes.

Two other people tested (AS and DB) showed significant threshold shifts at frequencies below 1000 Hz and accordingly performed worse than other test subjects with typical NIHL.

Audiometric results (average of left and right ears) for all NIHL-affected test subjects are summarized in Figure 55. Their test results relative to those of non-impaired listeners are also shown in the legend as a percentage, for S/N values ranging from 0 to +5 dB. Results listed are for either average C2/C3 scores for Boothroyd words or for meaningful phrases, whichever is applicable.

FIGURE 55:

Audiometric curves for all tested NIHL

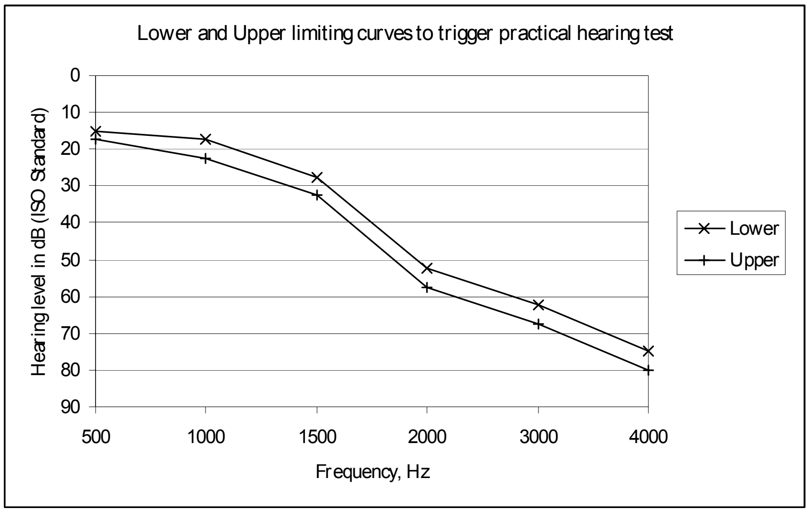


It is clear from the above Figure that both AS and DB have significantly higher threshold levels than the other test subjects at lower frequencies. From the remaining curves (where all participants scored 80 % or better relative to their non-impaired counterparts) Figure 56 shows the maximum threshold level at each frequency. This is called the "Upper" curve. Also shown is a "Lower" curve which represents threshold levels 5 dB (2.5 dB at 500 Hz) lower than the values in the Upper curve.

When a worker returns an audiometric curve with a threshold level lying between the Upper and Lower curves in any frequency band, then that worker is likely to perform at least 80 % as well as a non-impaired listener in a practical hearing test. The Lower curve should be adopted as the triggering level for a practical underground hearing test.

FIGURE 56:

Threshold level 'band' defined by Upper and Lower curves. A worker returning audiometric results in this band will perform 80% as well as person

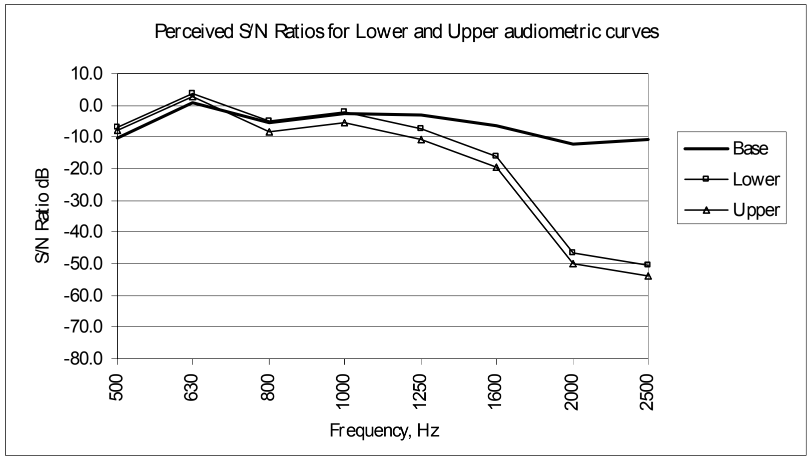


If a worker returned an audiometric result with the Upper curve for both ears, his binaural hearing loss would be equal to 27.2%. The Lower curve represents a binaural hearing loss of 22.5%.

Figure 57 shows perceived S_f/N ratios for the Upper and Lower curves in a pink noise environment where the overall S/N ratio is +5 dB.

FIGURE 57:

Perceived S/N levels in the underground environment for the Upper and Lower

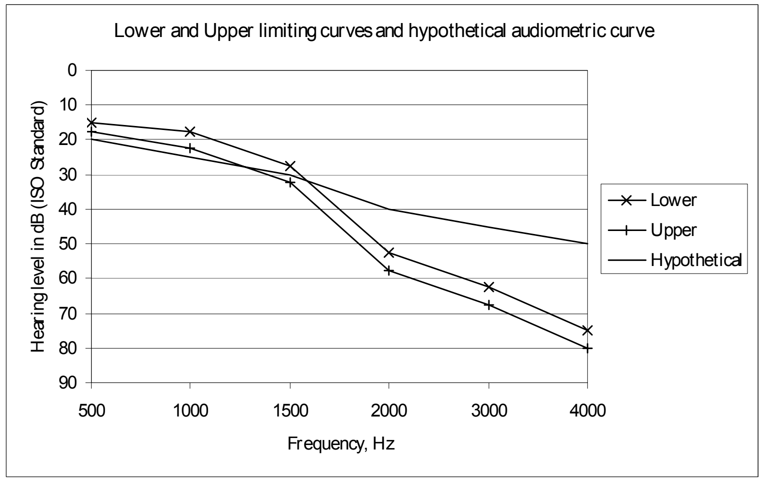


The important feature of this graph is that the impaired listener's high frequency loss reduces the overall background noise level slightly, with no threshold shift in the 630 Hz band, so that vowel sounds are actually heard at a slightly higher S/N ratio than for the non-impaired listener. The impaired listener's loss at around 1600 Hz to 2000 Hz greatly reduces his ability to hear single words in isolation, but other compensating factors lead to his being able to hear meaningful phrases about 80 % as well as a non-impaired listener.

Finally, consider the hypothetical audiometric curve in Figure 58. This person would appear to have suffered mild sensorineural hearing loss at all frequencies. The loss at higher frequencies appears to be typical NIHL, but the low-frequency loss is atypical for such a low level of high frequency loss and may be due to causes other than noise exposure.

FIGURE 58:

Hypothetical audiometric curve representing a

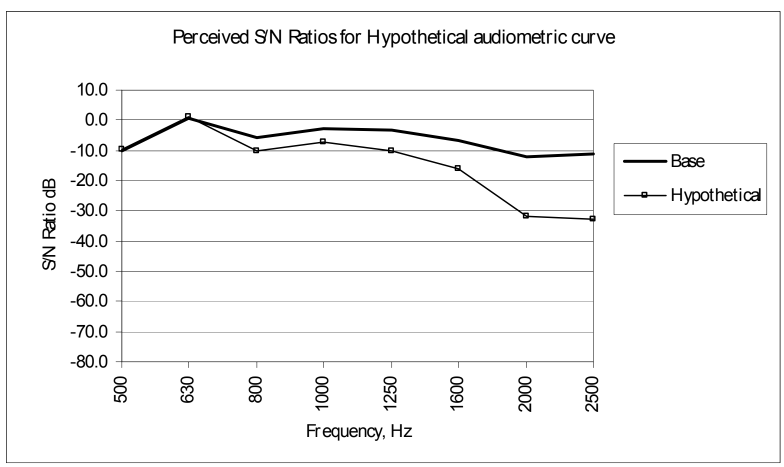


The hypothetical curve above represents a binaural hearing loss of only 17.1 %. This is 10 % less total hearing loss than the Upper curve of Figure 56, yet the person represented by the Upper curve is likely to score better on the practical hearing test.

Figure 59 shows perceived S_f/N ratios for the hypothetical curve above at an overall S/N ratio of +5 dB. Note that S_f/N is reduced by approximately 4 dB relative to the proposed limiting curves at the critical "vowel" frequencies. This is unlikely to be compensated for by the higher S_f/N ratios at "consonant" frequencies.

FIGURE 59:

Perceived S/N ratios for hypothetical



Practical test procedure

This concluding Chapter presents a summary of the procedure to follow for conducting a practical hearing test.

Requirement for a test

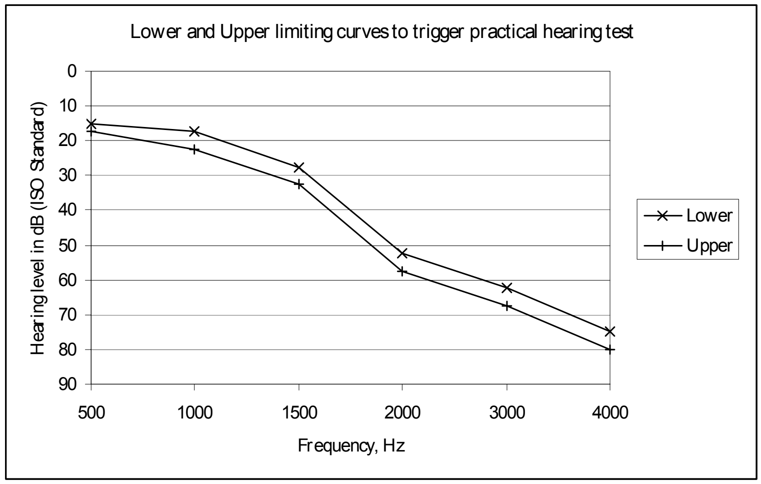
It is usual practice for a mine to have its workers' hearing tested every three years, via screening audiometry, in a campaign where all workers are tested within a period of approximately one month. These results are usually reviewed by the mine's OHS representative, who has previously needed to resort to subjective assessments to determine whether a worker with greater than 20 % binaural hearing loss is safe to continue normal duties.

The recommendation arising from this study is that the OHS representative should first compare each worker's audiometric results with the curves shown in Figure 56, reproduced below as Figure 60. If the test results show higher threshold levels in any frequency band than the LOWER curve of Figure 60 for either ear, then that worker should be subjected to the practical hearing test.

Note that the inclusion of the UPPER curve merely serves to highlight a hearing loss 'band' in which the impaired listener is likely to achieve 80% of the test score of a non-impaired listener. Any worker with threshold levels higher than those in the UPPER curve, particularly at the lower frequencies, should be sent for professional audiological assessment before participating in the practical test.

FIGURE 60:

Audiometric curves for triggering a



Recommended word lists

The following meaningful words and phrases were developed during the development of the practical hearing test. They are short phrases that may be shouted in an emergency situation and contain familiarity and emotional cues beyond the purely auditory cues present in words use for typical speech intelligibility tests.

These lists are certainly not exhaustive and additional lists may always be added, provided the words/phrases are short and meaningful to the worker being tested.

LIST 1
1. Where's the fire?
2. Is there anybody there?
3. Look out
4. What are you doing?
5. Stand still
6. Are you hurt?
7. What happened?
8. Stop the engine
9. Move over
10. Are you trapped?

LIST 2
1. Where's the deputy?
2. Hey, [name of participant]
3. Turn it off
4. What's that smoke?
5. Are you OK?
6. There's a gas leak
7. Don't panic
8. Find the radio
9. Walk this way
10. Hit the kill switch

LIST 3

LIST 4

1. Get down	1. Call for help
2. Everybody out	2. Is anyone missing?
3. Help me	3. Follow me
4. I need some light	4. Gasmasks on
5. Come here	5. Who's injured?
6. My leg's broken	6. Save yourself
7. Get help	7. Help that man
8. Where's the exit?	8. Don't move
9. Don't stand there	9. Can I help?
10. Can you move?	10. Stay calm

Suitable Test environments

The practical test may be conducted either underground or in a suitable room with a minimum of equipment and without the need for detailed post-processing, provided the test environment is carefully set up.

Details of appropriate above- and underground test environments are presented below. It is possible to more accurately control S/N ratios in the room environment, although testing underground may be preferable, as it represents the actual work environment.

Underground environment

It is recommended that underground testing be conducted in a development unit or some other place in the non-hazardous zone using a diesel-engined personnel carrier (PC) as a noise source. The PC should be set to rev at its normal operating level and a sound level meter used to determine the distances at which noise levels of 85dB(A) and 80 dB(A) are achieved. The sound level meter should be of the integrating type conforming to at least Type 2 requirements as set out in AS 1259 – 1990 *Sound level meters* Part 2: *Integrating - Averaging*.

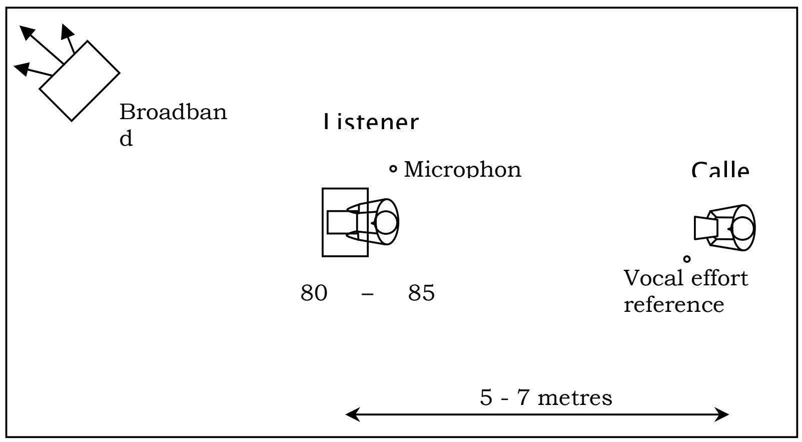
Room environment

Tests may be conducted in a room of dimensions 5 m wide by 12 m long, or larger. A portable broadband noise source with adjustable volume should be placed facing into a corner as shown in Figure 61 to produce a diffuse sound field. Suitable noise sources include pink or white noise generators, radio 'static' played through an audiovisual or PA system (if the room is set up with one) or even a large industrial vacuum cleaner.

A desk for the listener should be placed so that it is not too close to the noise source, while leaving at least 5 – 7 m distance to the caller at the other end of the room. The noise source is required to produce noise levels of 80 dB(A) and 85 dB(A) at the listener's desk. In the case of a noise source without volume control, this may be moved about to produce the required levels, and should be placed between the caller and listener locations.

FIGURE 61:

Schematic layout of room environment for practical hearing test



Conducting the test

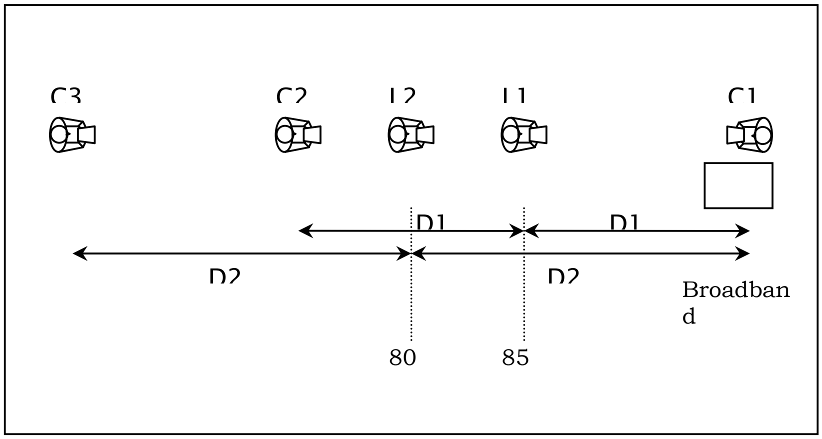
Underground environment

With the PC set at its operating revs, measure out and record the distances D1 and D2 at which the noise levels are 85 dB(A) and 80 dB(A), respectively. These distances are illustrated in Figure 62. With the listener standing a distance D2 (ie, in an 80 dB(A) environment) from the PC, the caller should first call one of the recommended words lists from next to the noise source (position C1), and a second list from a distance D2 on the 'quiet' side of the listener (position C3).

This process should be repeated with the listener in an 80 dB(A) environment (ie at a distance D1 from the source) so that four lists are called in total. The three caller positions (C1, C2 and C3) and two listener positions (L1 and L2) are also shown in Figure 62.

FIGURE 62:

Schematic layout and caller/listener positions for



Room environment

The sound level meter (SLM) must first be used to find a distance at which the caller's voice is approximately 80dB(A) at the listener's desk, in the absence of background noise. Maximum vocal effort will usually not be necessary for this level to be achieved. Next, some test words should be called with the same vocal effort and with the microphone only 1m from the caller. The measured level at this location will be much higher than 80 dB(A) and should be recorded so that, during the tests, the caller may look at the SLM to assist with maintaining a constant vocal effort.

Before conducting the test, the source noise volume should be adjusted to achieve 80 dB(A) at the listener's desk. When the caller has completed two of the recommended word lists the source volume should be increased to give 85 dB(A) at the listener's desk. The caller should then complete two more word lists with the predetermined vocal effort.

Assessment of results

In either the above ground or underground test, the impaired listener should score at least 80% of the score of a non-impaired listener. To make this determination it is necessary that a non-impaired, or minimally impaired, ‘control’ listener be included.

If this is not possible or desirable, then the test may be conducted on the impaired listener only. This study has found that non-impaired listeners will score an average of 95 % or more correct for meaningful phrases called in a broadband background noise environment where S/N is in the range 0 to +5 dB. It is therefore necessary for the impaired listener to score a total of 76 % correct in the absence of a control listener.

It is preferable to include a control listener in each test, as the relativity between test scores will not be greatly affected by inaccuracies in setting up the desired S/N ratios. For example, if S/N is not greater than -5 dB during the test, then the impaired listener may only score 70% correct, which constitutes a ‘fail’. Under these conditions, however, a non-impaired listener is likely to score around 88 %. The impaired listener has therefore scored the required 80 % of the non-impaired listener’s score and has ‘passed’.

A major feature of this assessment approach is that there are no complicated post-processing requirements. The OHS representative simply tallies up the scores and makes appropriate recommendations to the Mine Manager. These recommendations should be guided by the following considerations:

- If a worker ‘fails’ a practical test in which there was no control listener, then the results may be discarded and a second test including a control listener should be conducted.

- If a practical test includes a control listener and the control listener scores less than 85 %, then S/N values are likely to have been below the desired range (ie, the background noise was too high) and a second test should be conducted, unless the impaired listener scored *75 % or more*, in which case the worker has ‘passed’. If a second test is necessary, an acoustics professional should be engaged to ensure that the test environment is appropriately set up.

Failing the test

If a worker's audiogram (obtained by an audiological specialist) shows threshold levels greater than the Lower curve in Figure 58, and if that person subsequently fails the practical hearing test as outlined above, then that worker is likely to present a safety risk to himself and others due to his decreased ability to hear shouted warnings or instructions.

In this situation, a Mine Manager would be acting in the interests of worker safety by assigning that worker to other duties, if possible. For a worker who failed the hearing test by up to 5 percentage points, an environment in which the background noise level is below 80 dB(A) is likely to increase his ability to hear warnings to an acceptable level. Such environments include some underground areas away from the coalface and many above-ground areas.

At the Coalface

Noise levels well above 90 dB(A) occur at the coalface when the shearer is operating. For workers separated by more than a few metres, the S/N ratio for shouted speech in this environment will typically be -10 dB or less. Reference to Figure 53 suggests that a person with little or no hearing loss will score well under 50 % correct on a practical hearing test in this environment. Shouted warning signals are therefore rendered virtually useless at the coalface for impaired and non-impaired listeners alike and more visual forms of communication, such as body-language and even lip-reading, become much more important.

Without stepping outside the scope of this study by dwelling on the issue of the usage of hearing protection at the coalface, it is interesting to note that workers to whom this study relates are likely to have developed visual communication skills to compensate for their hearing loss.

It is therefore probable that a worker's hearing loss will not constitute a large reduction in his ability to communicate with other workers in the noisiest of environments.

In summary, a worker's high level of NIHL is not likely to reduce his communication skills to unacceptable levels, for safety purposes as compared with a non-impaired worker, in either quiet (<75 dB(A)) or very loud (>90 dB(A)) environments. In those areas where the noise level is between these values, the procedure detailed in this study may be used to assess the safety implications of a worker's NIHL.

Bibliography

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