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Development of New "Detectsound" - A Computerized Model for Adjusting
the Level of Acoustic Warning Signalization in the Workplace

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Master of Science Thesis

Development of new “Detectsound” –

A Computerized Model for Adjusting the Level of Acoustic
Warning Signalization In the Workplace

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Abstract

Noise is a major aggressor in the workplace. It is widely acknowledged that noise may be hazardous to health and may interfere with speech communication. Researchers have found that noise and noise-induced hearing loss can also compromise the audibility of warning signals. A computerized tool called “Detectsound” has been developed for predicting the capability of workers to detect auditory warning signals in noise and for providing an optimal adjustment of signal levels according to the functional limits of the target worker(s). This work represents a comprehensive revision and improvement over an earlier version of the “Detectsound” model [Laroche et al. (1991), *Applied Acoustics*, 32, 193-214]. The main enhanced features are: (1) taking into account the hearing status for individuals, (2) incorporating the normative data describing the effect of noise exposure and age on hearing thresholds (ISO 1999, ISO 7029), (3) integrating more recent and accurate data on frequency selectivity, and (4) improving the user interface for the implemented software program. The revised “Detectsound” can be more easily applied to analyze the perception of warning signals for a specific individual, a group of individuals, or a target population based on their measured or estimated hearing status. The predictions of “Detectsound” have been validated against measured masked threshold data obtained in an ongoing laboratory study. For both individual and specific populations with normal hearing, the predictions fit measured data very well. A comparison between the original and new “Detectsound” shows that the predictions of the new “Detectsound” are closer to measured data. New “Detectsound” can be very useful in the situations when hearing protectors need to be accounted for, and when warning signals are to be optimized simultaneously for a range of individuals. Further work should include the integration of a sound propagation model for estimating noise distributions and optimizing warning signal perception over an entire industrial work area. The effect of noise type should also be considered in addition to noise level to reflect the difference in the efficiency of human in detecting target sounds in background noises of different temporal patterns. The relationship between hearing loss and frequency selectivity decrease may also need further review [Work funded under an NSERC Collaborative Health Research Project Grant, Canada].

Chapter 1. Introduction

1.1. Noise and workplace safety

Noise is a major aggressor in the workplace. Indeed, aging and occupational noise are the most prevalent causes of hearing loss in the male population (17/1000 males in both cases: Phaneuf and Héту, 1990). In 1994, the CSST (Commission de la santé et de la sécurité du travail du Québec) reported that noise induced hearing loss accounted for 69.5% of all occupational diseases. This situation is however not limited to the Province of Quebec. All industrialized countries encounter the problem of noise in the workplace (Berglund and Lindvall, 1995). In many European countries, regulations favor the use of techniques that aim to control the noise level at its source, but all too often in North America, we limit our practices to the use of hearing protectors to reduce noise exposure. In the last decade, we have moved towards the use of hearing protectors that attenuate noise less efficiently in order to ensure the workers' safety (Berger, 1991). Researchers and health/safety professionals have realized that earplugs and earmuffs that attenuate sound too efficiently can compromise the audibility of warning signals (i.e. fire alarms, sirens, bells) and speech communication, especially for workers affected by an occupational hearing loss (Suter, 1992). For example, in a study carried out in a steel plant (Tran Quoc et al., 1992), 93 different conditions where warning signals are used were surveyed. Results revealed that in 40% of the cases, the signals were not properly adjusted to effectively warn of safety hazards when hearing protection was worn. In other instances, the warning signals were deliberately set at excessively high levels, resulting in extremely aversive signals and disrupted speech communication when a signal was presented. Signal levels can sometimes be reduced by 20 dB (Patterson and Milroy, 1980). These facts have reinforced the idea that to ensure the safety of workers, and to protect them from the adverse physiological and psychological effects of noise exposure, it is preferable to control noise at the source, or at least to limit its propagation.

Organizations focusing on health and safety in the workplace are thus progressively more concerned with safety aspects. As a matter of fact, in Quebec, work related accidents represent more than 90% of the yearly compensable cases. Realizing

that a hearing loss and the presence of noise can affect communication and auditory signal perception, it can be questioned whether these conditions are partially responsible for accidents occurring in the workplace. Some studies have addressed this issue and seem to demonstrate a causal link between noise, auditory deficiency, and accidents in the workplace (Moll van Charente et al., 1990; Straub, 1974; Wilkins and Acton, 1982; Kilburn et al., 1992). In one such example, a worker lost a foot after failing to hear a signal indicating that a molten metal rod was approaching him.

1.2. Modeling auditory perception and sound propagation in workplaces

Faced with the serious problem of noise and safety in the workplace, two research teams have developed auditory perception models for warning signals (Laroche et al., 1991a, 1992) and sound propagation models at industrial sites (L'Espérance, 1987, 1999, 2000). A significant outcome of work conducted by the first team was the development of the software tool called "Detectsound", which can be used to predict the capability of workers to detect auditory signals in noisy worksites. Efforts from the second team are represented by "OUIE-2000", a sound propagation model that is used to predict the level and spectrum of noise at any point in a given industrial setting.

The first team represents research efforts from psychoacoustical and physiological fields, and focuses on human sound perception characteristics (Laroche et al., 1991, 1992; Giguere et al., 1994,1999; Patterson et al., 1995), whereas the second team mainly concentrates on the acoustical aspects of this problem. The "Detectsound" model is useful to specify the target characteristics of warning signals (sound level and spectral content) reaching worker's ears. However, it cannot predict what the characteristics of the warning devices should be in order to achieve these targets once installed on the walls or ceilings in the workplace. "OUIE-2000" can predict the noise distribution in a room, but is currently unable to predict the audibility of an added sound (such as a warning signal).

1.3. An approach to the installation of warning devices in the workplace

Although the "Detectsound" and "OUIE-2000" models were developed separately, it is possible to integrate them into a single tool after certain modifications and improvements are made within each model. "Detectsound"'s predictions are based on

noise levels and spectra at specific workstations, which are currently obtained by measurements using a sound level meter. In an integrated model, “OUÏE-2000” could provide these values directly to “Detectsound”. “OUÏE-2000” is powerful at predicting noise distribution characteristics at worksites. With the integration of “Detectsound”, it will also be able to predict the audibility of sounds (like warning signals) embedded within that noise. Such an integrated model will provide a complete tool for the installation of warning devices in noisy worksites, which could be an important aspect of improving workplace safety. As strongly encouraged by a consulting group of hygienists, audiologists and engineers specialized in acoustics (L’Espérance, 2000), the project reflects a joint effort from the two research teams toward integrating their models. Figure 1.1 illustrates the proposed approach for integrating the two models. This project has been funded by NSERC (Natural Sciences and Engineering Research Council of Canada).

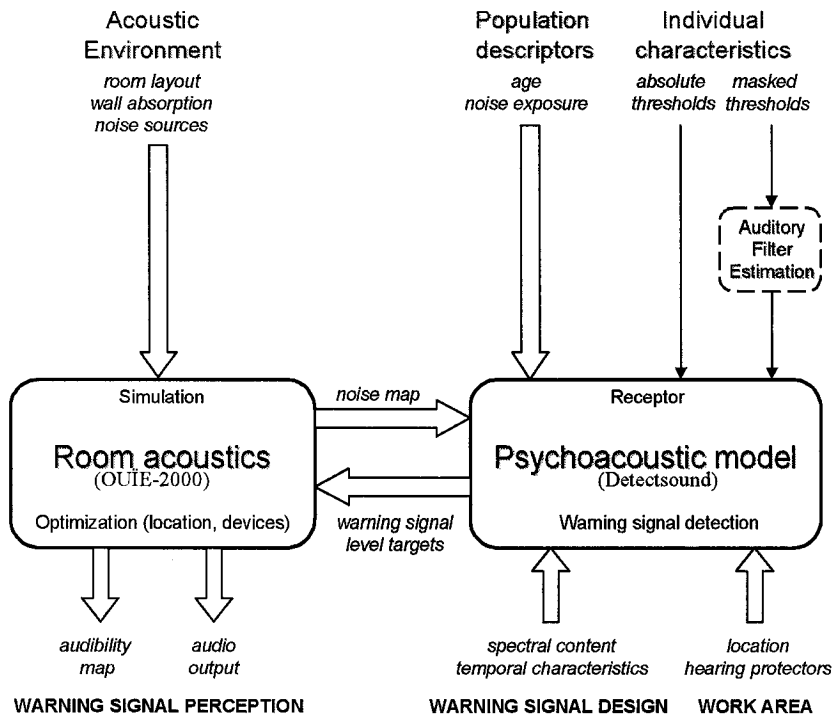


Figure 1.1: The project of optimizing acoustic warning signalization in noisy industrial settings

The main objectives of the overall project are: (1) to develop a signal audibility model that takes into account the hearing status of individual workers (absolute

thresholds, auditory filters) or target populations (age, noise exposure), (2) to develop a sound propagation model for noisy industrial settings that can map out the zones where acoustic warning signals are audible, and (3) to integrate both models into a tool that can help specify the optimal solution for the installation of acoustic warning devices in a given setting, in terms of number of devices to be used, as well as their optimal location and output level.

The sound propagation model (OUIE-2000) is used to predict and map the noise distribution (level and spectral content) in a given industrial setting (Figure 1.1). This prediction is based on knowledge of the room's layout, the acoustic absorption characteristics of the walls, ceilings and floors, and the location, number and sound power level of the noise sources in the room. Additionally, acoustic baffles and barriers set in place in the environment to reduce noise exposure can be taken into account to reflect accurately the noise characteristics at each workstation.

The psychoacoustical model (Detectsound), in turn, takes into account the noise distribution in the room to specify the acoustical characteristics associated with an optimal warning signal (frequency range, level) at each workstation (Figure 1.1). The characteristics of the optimal warning signal specified by the psychoacoustical model can be tailored to meet the needs of an individual worker or given population of workers. In the former case, the model will take into account the absolute hearing thresholds of the worker as a function of frequency (measured with an audiometer) as well as the auditory frequency selectivity (derived from notched-noise masked thresholds). Where needed, it will also be possible to tailor the specifications of the optimal warning signal to a statistical population of workers. In this case, absolute hearing thresholds will be based on the latest normalized data on the effect of age (ISO 7029) and noise exposure (level, exposure in years) (ISO 1999) on hearing. Additionally, recent data on the change in frequency selectivity with hearing loss (Laroche et al., 1992; Moore and Glasberg, 1997) will be incorporated into the psychoacoustical model. Finally, it will be possible to account for the effects of wearing a hearing protector, like an earmuff or earplug, on the specification of the optimal warning signal.

The final step is a return to the sound propagation model (OUIE-2000) to simulate potential scenarios for the installation of warning signal devices (or speakers). This step

is necessary because warning signal devices cannot be located right beside each worker in actual practice. The devices must generally be installed on walls or ceilings, often at a considerable distance from the targeted workers. The sound propagation model will be used to select the minimal number of devices needed, and their location on walls, to ensure audibility of the warning signal at each workstation, given the specifications provided by the psychoacoustical model. For this purpose, the model will trace a two-dimensional audibility map of the industrial setting where the specifications of the psychoacoustical model are met, and therefore where the warning signal can be heard optimally. Finally, the model will be able to generate an audio output of the noise and warning signal at any desired location in the industrial setting. This will enable the verification of the warning signal's audibility by the targeted worker or population of workers via headphones, prior to installation.

1.4. Objectives of the thesis

The present research's main focus is on the development of the psychoacoustical model. The original version of "Detectsound" (Laroche et al., 1991) provides a good prototype for this work. The new model will reflect improvements in the following aspects:

- The processing algorithms to account for the hearing status of **specific individuals** will be expanded, particularly with respect to frequency selectivity measurements.
- Normative data (ISO 1999, ISO 7029) for estimating auditory sensitivity according to age and noise exposure will be incorporated into the new model. The improved model will be able to predict the sound perception characteristics of **specific populations** based on their estimated hearing status.
- Recent research findings on the relationship between frequency selectivity and hearing loss, and between frequency selectivity and signal detection will be incorporated. The new model will have better predictability for populations with hearing loss, and for individuals with known frequency selectivity.
- A software tool will be developed or extended to implement the established psychoacoustical model. User friendliness will be at primary concern with the

software tool. A comprehensive database will be built in to support the storage and retrieval of analysis information.

1.5. Organization of the thesis

The thesis aims at developing an improved model for adjusting the level of acoustic warning signalization in the workplace. The research work included in the thesis is structured in several chapters. Chapter 2 reviews the pioneering work on this topic and some recent advancements on important aspects related to modelling. Chapter 3 deals with the design and implementation of the improved model. Chapter 4 provides some validations for the new model developed in the present research. Chapter 5 details and discusses some applications of the new model. Chapter 6 summarizes the main findings from the present work and addresses some problems and improvements that should be considered in the future.

1.6. Thesis contribution

This thesis is part of a larger research project on the optimization of acoustic warning signals in the workplace. The present work focuses on the algorithmic development of a model for predicting the detection of acoustic warning signals. Through a comprehensive improvement over an original model on this topic (Laroche et al., 1991), this thesis has contributed to:

- Expanding the application of the model to individual worker(s);
- Allowing more accurate predictions by including some recent research findings on frequency selectivity and implementing a direct estimation method for masked thresholds;
- Providing means of estimating hearing sensitivity based on aging and noise exposure;
- Further developing an implementation software tool for better user friendliness

In the context of the present thesis, the model for predicting the noise distribution within workplaces (OUIE-2000), though mentioned occasionally and strategic for further developments, is not an integral part of the research contribution.

Chapter 2. Theoretical foundations

2.1. Auditory perception: concepts and definitions

Auditory perception is determined by the interaction of sound waves with the human hearing system. Some psychoacoustical concepts and acoustical terms frequently used in the present research are summarized below (Moore, 1997; Pickles, 1988; Ballantyne, D., 1990; Bess, F.H. & Humes, L.E., 1990; Moller, A.R., 2000).

Sound wave or signal: Rapid disturbance or fluctuation of air particles propagating in space. Sound waves are represented by tracing the amplitude of the disturbance as a function of time (at a fixed point) or space (at a given time).

Sound pressure: A measure of the amplitude of a sound wave at a given point expressed in terms of the pressure deviation (in Pascals or Pa) from the static or ambient pressure. The human auditory system can deal with a wide range of sound pressures. A logarithmic or dB scale expressing the ratio of two pressures (the actual pressure and a reference pressure) is often used to quantify the amplitude of a sound wave.

dB SPL (sound pressure level): A value in decibel which expresses the logarithm of the pressure P of a sound wave in relation to a reference pressure ($P_0 = 20 \mu P_a$) according to the following:

$$\text{dB SPL} = 20 \log_{10}(P/P_0).$$

By definition, a sound pressure $P=P_0$ corresponds to 0 dB SPL, a sound pressure reference which was chosen to be close to the average human absolute threshold at 1kHz.

Spectrum: Representation of the amplitude distribution (in Pa or dB) as a function of the frequency components within a sound wave or signal.

Octave band analysis: A spectral analysis where the amplitude of the sound wave is measured at a series of frequency bands, each being one octave wide.

Third-octave band analysis: Same as above, but analysis is performed over frequency bands that are one-third of an octave wide.

Outer ear: The outer ear is composed of all the anatomical structures (head, pinna, ear canal) that contribute to the transmission of an incoming sound from the free field to the eardrum (tympanic membrane). The outer ear produces a “sound pressure gain” at the eardrum with respect to the free field. This sound pressure gain is both frequency and direction dependent, and is an aid to sound localization. It can reach 15 – 20 dB at 2.5 kHz for laterally incident sounds (Shaw, 1974). See Figure 2.1.

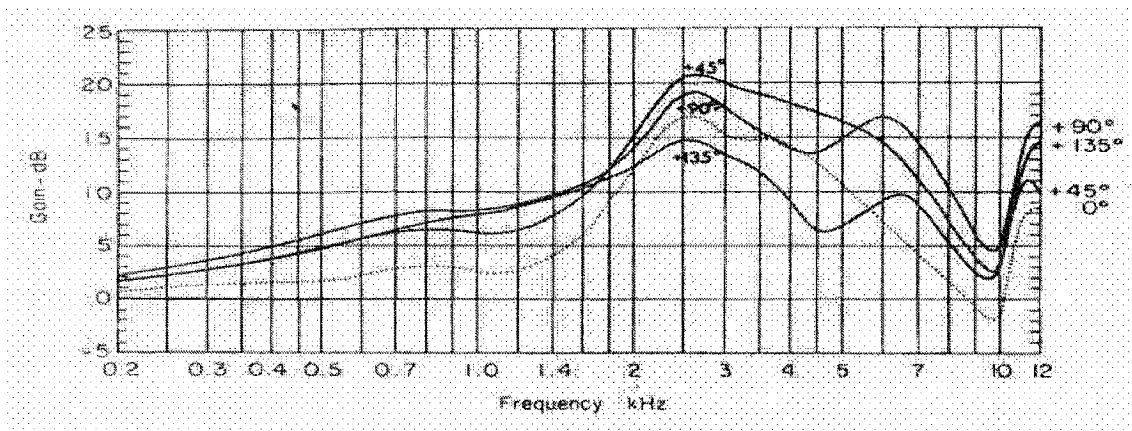


Figure 2.1: The average pressure gain (or transfer function) of the outer ear in man. The pressure gain at the eardrum over that obtained in the free field is plotted as a function of frequency. Zero degree represents a signal approaching from directly in front, whereas $+90^\circ$ indicates a signal approaching from the right side (from Pickles, J.O., 1988, Fig. 2.2).

Middle ear: The middle ear includes all the anatomical structures (eardrum, ossicular chain, cavities) involved in the transmission of sound from the eardrum to the entrance of the cochlea (inner ear). The middle ear transforms the sound pressure variations of the ear canal into a sound pressure variation in the cochlea in a frequency-dependent manner. At 1 kHz, the sound pressure is 30 dB greater than that at the eardrum. See Figure 2.2.

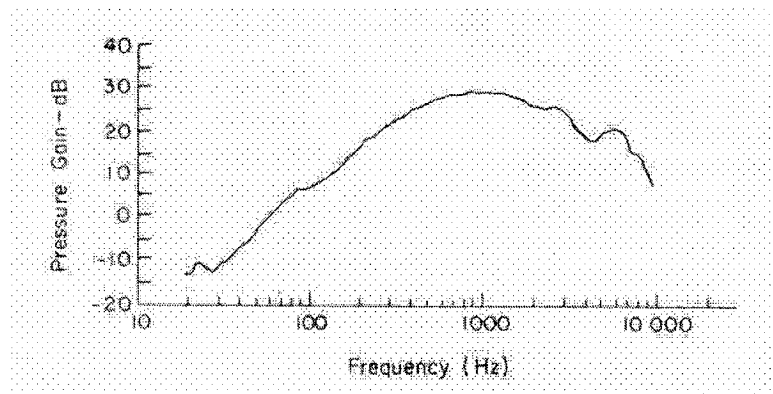


Figure 2.2: Transfer function of the middle ear. The pressure gain in the cochlea over that measured at the eardrum is shown as a function of frequency (from Pickles, J. O., 1988, Fig.2.6)

Transmission factor: In the context of the present work, it accounts for the transmission of sound through the outer and middle ear. In order to properly calculate the sound levels reaching the inner ear, the incoming sound level (dB SPL) must be corrected with this transmission factor (dB).

Inner ear: The inner ear or cochlea is a rigid, bony, snail-shaped structure involved in one of the major stage of sound analysis and transformation by the auditory system. The cochlea is filled with an almost incompressible fluid and is divided along its entire length by Reissner's membrane and the basilar membrane. The basilar membrane is especially interesting in the context of the present research as each section of this membrane only responds to a limited range of sound frequencies. The range of frequencies to which these sections are sensitive gradually decreases from the base (entrance) to the apex (end) of the cochlea. Inner hair cells (IHCs) and outer hair cells (OHCs) are also involved in the frequency analysis and transduction of sound into electrical activity in the auditory nerve. Processing by the inner ear is the primary physiological basis for frequency selectivity in human hearing.

Absolute threshold: The absolute threshold corresponds to the minimum detectable level of a sound in the absence of any other external sounds. It is generally measured using headphones in a sound-treated room and is expressed in dB HL. If it is measured by

presenting sounds to a listener through loudspeakers and then measuring the sound pressure level by placing a microphone at the centre of the position that had been previously occupied by the subject's head, the absolute threshold is called the MAF (minimum audible field). See Figure 2.3.

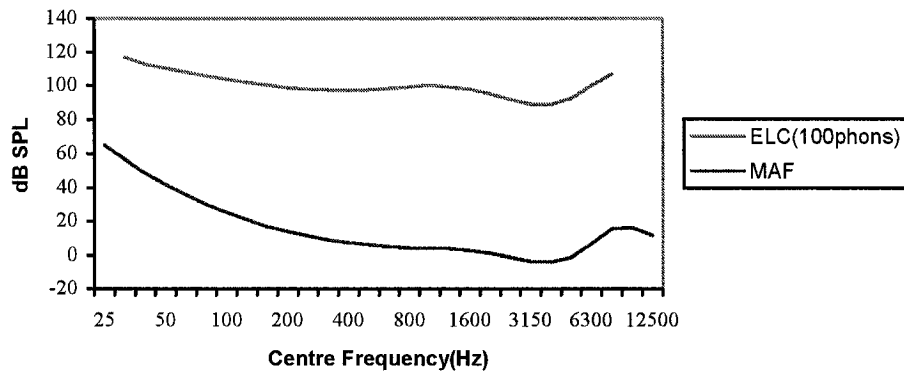


Figure 2.3: MAF curve and ELC contour at 100 phons (from ISO 226, 1987).

dB HL (hearing level): This term expresses the minimum level at which a person can detect a sound at a specific frequency in relation to a reference value (0 dB HL). This reference value represents the average absolute threshold in normal-hearing subjects. Thus, a threshold of 40 dB HL at 1kHz would mean that a person has an absolute threshold that is 40 dB higher than “normal” at 1kHz.

Masking: It refers to the property of one acoustic signal to obscure the presence of another sound, thus making the later more difficult to detect.

Masked threshold: The masked threshold of a sound (or target) is the level at which it is just detectable in the presence of some other sound (or masker). It depends on the characteristics of the masking sound (level, frequency, etc.).

Loudness: Loudness is the perceptual correlate for the intensity or force of an acoustic stimulus. Increasing intensity is generally associated with increasing loudness, however there isn't a simple one-to-one relationship between the two. Loudness is usually quantified by two terms:

phon: It is a relative measure of loudness. The loudness level in phons of a given sound is equal to the level in dB SPL of a 1 kHz tone that is perceived equally loud.

sones: It is a measure directly proportional to perceived loudness. By definition, 1 sone is the loudness of a 1kHz tone presented at 40 dB SPL.

ELC (Equal Loudness Contours): It consists of a series of curves used to represent how much sound pressure in dB SPL is required to make tones of different frequencies appear equally loud. These contours are normalized in ISO 226 for a range of loudness levels in phons (see Figure 2.3 for the 100-phon contour).

Frequency selectivity: It refers to the ability to resolve the individual frequency components in a complex sound, and plays a major role in many aspects of auditory perception. It is generally believed that masking reflects the limits of frequency selectivity; if the selectivity of the ear is insufficient to separate the signal from the masker, then masking will occur. Frequency selectivity of the ear is usually described in terms of auditory filters. The narrower the auditory filters, the greater the ability to separate sounds of different frequencies.

Auditory filter, critical band, ERB: In the science of hearing, an incoming sound is often treated as though it is passing through a bank of band pass filters, called **auditory filters**. The bandwidth of human auditory filters at different frequencies can be measured psychoacoustically in masking experiments. The results of traditional masking experiments using narrowband noise masker refers to the width of an auditory filter at a particular frequency as the **CB** (Critical Band); more recent research using notched noise as masker lead to the term **ERB** (Equivalent Rectangular Bandwidth). In general, individuals with hearing loss (elevated absolute thresholds) have wider auditory filters than normal-hearing individuals.

Bark scale and ERB-rate scale: These are two auditory scales of frequency representation. The **Bark scale** uses CB as a natural scale unit. It usually ranges from 1 to 24, corresponding to the 24 critical bands of hearing. Because measuring the critical

bands below 500 Hz appeared to be quite difficult, more recent and accurate measurements of auditory-filter bandwidths using notched-noise maskers have now lead to the ERB-rate scale, which ranges from 1 to 40. In general, the auditory-filter bandwidths on the **ERB-rate scale**, expressed in equivalent rectangular bandwidth (ERB), are smaller than that of the Bark scale, a relative difference which becomes larger for lower frequencies.

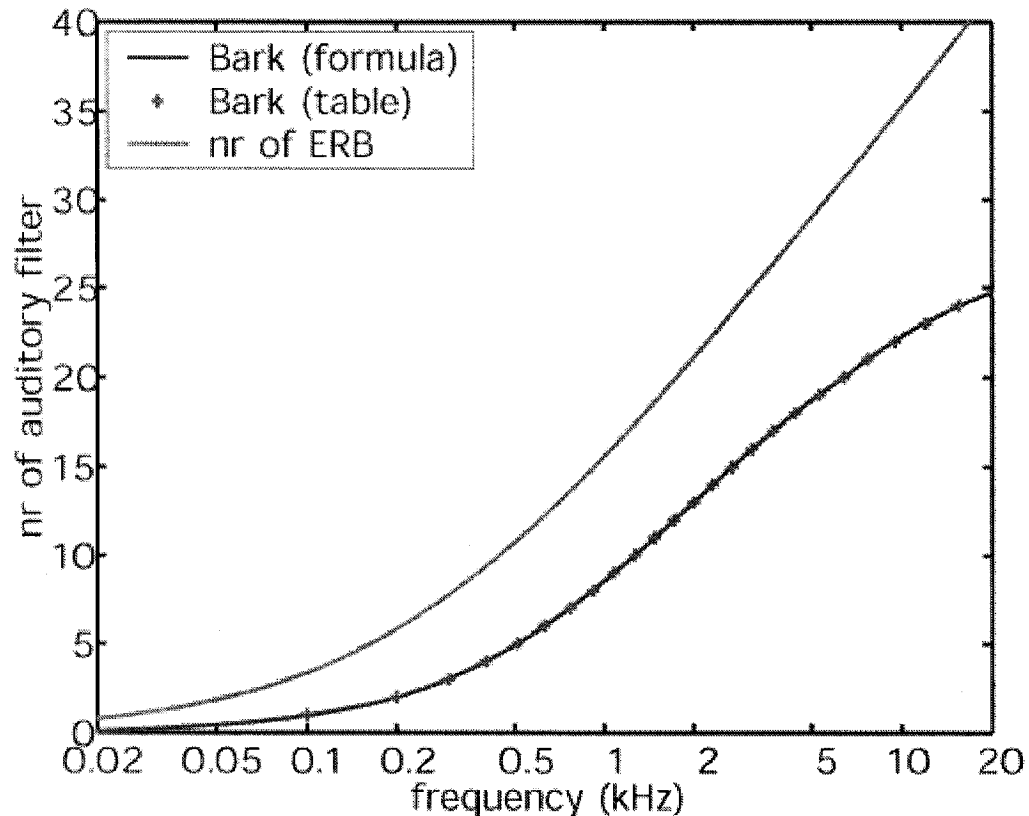


Figure 2.4: Bark scale and ERB-rate scale (from online course notes by Dik J. Hermes & Maxim Schram, <http://www.ip0.tue.nl/homepages/dhermes/lectures/SD/ChII.html>)

Excitation pattern: The excitation pattern for a given sound is defined as the distribution of the outputs from the auditory filters as a function of their centre frequency. Note that excitation patterns have the same general form as masked audiograms.

Hearing protector: Equipment or device used for protecting workers against loud noise. When worn, it reduces the sound level reaching the outer ear. The characteristics of hearing protectors are generally expressed in terms of the attenuation degree in dB over a

range of third-octave frequency bands. The two main types of hearing protectors are earplugs (inserted in the ear canal) and earmuffs (cups enclosing the ears).

2.2. Prototype for the present research: “Detectsound”

Sound detection in interfering noise has been well documented in the past decades (Zwicker, E. & Scharf, B., 1965; Moore, B.C.J. & Glasberg, 1996; Moore, B.C.J., Glasberg, B.R. & Baer, T., 1997). In theory, a signal will be detectable if its level is no less than 4 dB below the level of the noise at the output of the relevant auditory filter (Moore, B.C.J., 1997). Unfortunately, detection is not the only factor to consider while designing warning signals. Other features should include the degree to which the signal: (1) attracts attention, (2) is recognizable among other sound signals (Wilkins, P. & Martin, A.M., 1987), and (3) is moderately loud. In practice, a level of 10 to 15 dB above the masked threshold has been proposed as an acceptable level (Wilkins, P. & Martin, A.M., 1987; Patterson, R.D. & Milroy, R., 1979; ISO 7731, 1986). While this principle is well established, there are practical problems concerning its application in real situations. It can be very difficult for health and safety personnel to evaluate the efficiency of warning signals in the field, due to restrictions in training and access to specialized sound measurement equipment at worksites. “Detectsound” (Laroche et al., 1991a; Tran Quoc et al., 1992) seems to be the first practical software tool for predicting detectability of warning signals.

“Detectsound” has been developed to predict the audibility of warning signals in real-life conditions. This model takes into account the hearing status of the target population; it is one of the few practical tools that integrate both reduced hearing sensitivity and frequency selectivity (Laroche et al., 1992) normally associated with hearing loss. The effects of wearing hearing protectors on signal detection in noisy workplaces can also be taken into consideration (Laroche et al., 1991a). The model has been extensively used to assess the audibility of warning signals such as sirens, buzzers, bells, and reverse alarms by workers in noisy workplaces (Laroche et al., 1991a,b; Laroche and Lefebvre, 1998) and fire alarms by occupants of apartment buildings and offices (Proulx et al., 1995). Consequently, the model has been used to design safer warning signals and to propose modifications for existing signals in term of spectral

content and overall sound pressure level. The model not only addresses the requirements for detectability of warning signals, but also the problem with recognition or identification of warning sounds (Hétu & Tran Quoc, 1994). The flow chart of “Detectsound” is as follows:

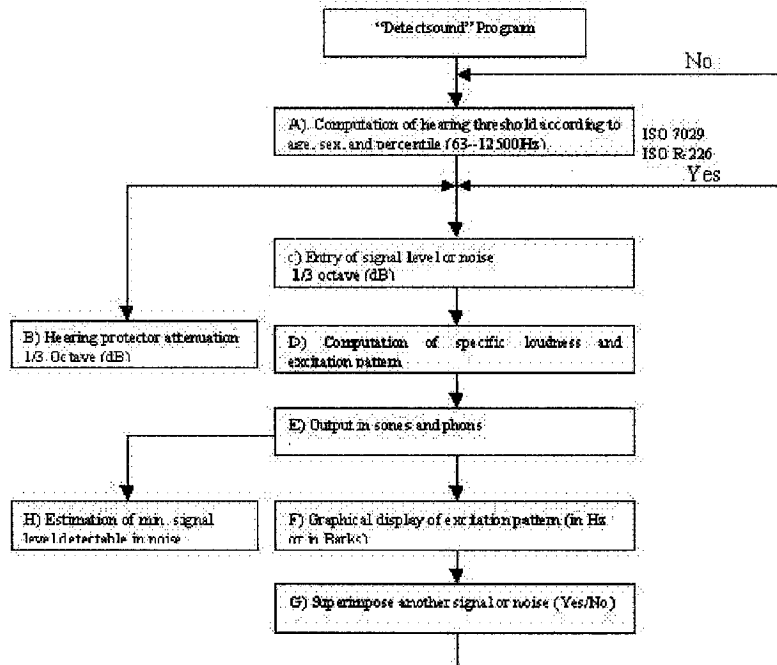


Figure 2.5: Flow chart of the “Detectsound” program (from Laroche et al., 1991)

The main algorithm behind “Detectsound” was based on the loudness perception model by Zwicker and Scharf (Zwicker, E. & Scharf, B., 1965). The computation of loudness of signals and background noise involves five steps: (1) correction of signal and noise levels in order to take into account the attenuation due to hearing protectors if worn (Figure 2.5, part B), (2) entry of signal or noise level with corrections to compensate for the transmission factor (Figure 2.5, part C), (3) calculation of the excitation levels in the auditory system (Figure 2.5, part D), (4) calculation of the specific loudness (Figure 2.5, part D), and (5) calculation of the total loudness in sones and phons (Figure 2.5, part E). These five steps are repeated for each signal and noise (Laroche, C. et al., 1991).

(1) Correction for hearing protector attenuation

After the signal or noise levels are entered, the attenuation provided by the specific hearing protector (if worn) is accounted for. Typically, only attenuations at 63,

125, 250, 500, 1000, 2000, 4000, 8000Hz are measured (or estimated). A series of extrapolations and interpolations are thus made at this stage to estimate the attenuations for 28 one-third-octave frequencies ranging from 25Hz to 12500Hz. These values are then subtracted from noise and signal levels to reflect the actual sound levels reaching outer ear when a hearing protector is worn.

(2) Correction for outer and middle ear transmission

“Detectsound” assumes a transmission factor of 0dB for all frequencies below 1000Hz. Above this frequency, the transmission factor parallels the curve relating sound pressure level with frequency for normal absolute hearing thresholds (Laroche et al., 1991). The absolute hearing threshold at 1000Hz is considered to represent the level of internal noise within the auditory system; the transmission factor at all frequencies above 1000Hz is defined by subtracting the absolute threshold at 1000Hz from the absolute threshold associated with that frequency. For example, the absolute thresholds (Minimum Audible Field) at 4000Hz and 1000Hz are -3.9 dB and $+4.2$ dB respectively. Therefore the transmission factor at 4000Hz is $-3.9 - 4.2 = -8.1$ dB.

In actual implementation, a series of specific corrections was also carried out for frequencies below 400Hz to account for the variable shape of the equal-loudness contours in this frequency range. After these corrections, the obtained noise level obtained is assumed to represent the input level of noise reaching the inner ear.

(3) Calculation of the excitation levels

At this stage, “Detectsound” followed the calculation principles proposed by Moore and Glasberg (1987). The excitation level at a given frequency corresponds to the response or output of the auditory filter centered at this same frequency. The filter shapes are based on the masking curves proposed by Zwicker and Scharf (1965). The bandwidth of each filter (measured at -3 dB) is assumed to be equal to the critical bandwidth centered at one frequency.

At high frequencies, slope for the these filters is 27dB/Bark, whereas the low frequency slope was decided by the following function:

$$Slope_{inr} = (0.125 * L_i + 17.5) \text{ dB/Bark}$$

where L_i denotes the sound pressure level of the signal or noise.

Filter bandwidth (measured at -3dB) is adjusted as a function of age according to the following functions:

$$\Delta f = 15.0434f^2 + (79.8854 + \%_{inc} * 10^3)f + 79.0643$$

$$\%_{inc} = (0.002 \times age - 0.04)$$

where f is the centre frequency of the auditory filter, Δf represents the critical bandwidth, age is the age of the target population (must be above 20), $\%_{inc}$ denotes the increase in the critical bandwidth due to aging. The output level produced by noise (or signal) in a critical band is then computed from the noise or signal input levels entered in third-octave bands. This output is referred to the excitation level E in step 4 below.

(4) Calculation of specific loudness

Once excitation levels for each critical band are known, the specific loudness is computed according to the following formula proposed by Zwicker and Scharf (1965),

$$N'(sone/Bark) = 0.08(E/E_0)^{0.23} * [(1/2E/E_t + 1/2)^{0.23} - 1]$$

where E_0 = reference excitation level; E_t = excitation level at threshold; E = excitation level produced by the signal or noise.

E_t is assumed to be related to the internal noise. It is equal to the absolute hearing thresholds for frequencies lower than 1000Hz. For frequencies above 1000Hz, it is determined by the absolute hearing threshold minus the transmission factor. Excitation level E is computed in step 3 above.

(5) Calculation of total loudness

As suggested by Zwicker and Scharf (1965), total loudness is the integral of the specific loudness over the z scale in Barks. The excitation pattern is computed from excitation levels in the 20 critical bands fallen between 63 and 12500Hz. The summation of many excitation levels at a given frequency is made according to an intensity law. The total loudness is expressed in sones and phons.

The efficiency of signals to act as warning sounds in noise can be determined by comparing the excitation patterns they generate. As suggested by other researchers (Coleman et al., 1980; Wilkins et al., 1987), a level of 12dB above masked thresholds was used in “Detectsound” as a guideline to set the lower boundary for warning sound levels. “Detectsound” facilitates the adjustment process by producing a design window (or conception window). For a specific frequency, this window’s lower boundary is

defined as 12 dB above the masked threshold (or 105 dB SPL, whichever is less); and its upper boundary is set at 13 dB above the lower boundary (or 105 dB SPL, whichever is less). If the level of a warning signal would fall below the lower boundary of the design window across all frequencies, it would be considered inefficient or too soft. If the level of a warning signal falls within the conception window at one or more frequencies, it will be judged as being efficient. Of course, in the case where the signal level surpasses the upper boundary of the design window at one or more frequencies, the signal will be regarded as overly loud. Such signals are undesirable in the workplace since they can trigger a startling response or adverse reaction.

The predictions made by “Detectsound” model have been validated by field studies. In a study by conducted Hétu and Tran Quoc (1992), researchers found that “Detectsound” “...generally leads to slight overestimation of the masked thresholds, the average error of prediction being smaller than 2 dB... Consider the guidelines for auditory warning signal design prescribing signal level adjustment at 15 dB above the estimated masked thresholds in order to ascertain attention demand and facilitate signal recognition...” it is feasible to apply “Detectsound” in industrial workplaces.

2.3 Limitations of the former “Detectsound” model

Despite its success in the past decade, the original “Detectsound” model has some limitations in application.

2.3.1. Application to a specific individual

There is a great need for a software tool like “Detectsound” to be applied to individual situations. In many workplaces, field safety supervisors need to know if a warning signal is efficient for a specific worker, or if the placement of warning signals is appropriate for all workers.

Unfortunately, “Detectsound” presently cannot be applied to individual situations. The frequency selectivity data that have been integrated into “Detectsound” were derived from normative data (Laroche et al., 1991a). As shown in Section 2.1, frequency selectivity refers to the ear’s capacity to perceive auditory signals in a noisy background,

and it is usually expressed as auditory filter bandwidths. “Detectsound” used average filter bandwidth data obtained from other studies. These bandwidths were associated to average auditory thresholds and cannot be adapted to a particular individual. Thus, predictions cannot be applied to a specific individual (Hétu and Tran Quoc, 1992). This means that even if one can measure the auditory thresholds and frequency selectivity characteristics of an individual, we are still unable to use the data to predict accurately the detection of a warning signal with “Detectsound”. This has greatly limited its application in practical workplaces.

One of the reasons for not including individual frequency selectivity data in “Detectsound” may have come from the cumbersome procedure of measuring individual auditory filters. A clinical tool had been developed to derive the auditory filter parameters (Hétu and Tran Quoc, 1992), but it is not practical due to limitation in required equipment and signals. Presently, a revised tool is under development in our laboratory. It is more practical in deriving individual frequency selectivity and the auditory filter parameters measured for specific individuals will be completely compatible with the revised version of “Detectsound” model.

2.3.2. Normative data on absolute threshold estimation

For a given workplace, “Detectsound” requires measured auditory thresholds data of the different workers. It is well known that measuring hearing thresholds is a very specialized operation. The examiners need some special training: instruments like audiometers are needed. And it can only be done in a very quiet environment (like in a sound-proof room). Thus, it is not practical in many workplaces.

Fortunately, estimation procedures are now available. Some international standards have provided very useful ways of estimating hearing thresholds of industrial workers. ISO 1999 (Acoustics – Determination of occupational noise exposure and estimation of noise-induced hearing impairment, 1989) and ISO7029 (Acoustics – Statistical distribution of hearing thresholds as a function of age, 2000) are two such tools. ISO 1999 describes the empirical relationship between noise exposure and the “Noise-Induced Permanent Threshold Shift” (NIPTS), and ISO7029 specifies the hearing

threshold level associated with age. Together, they provide procedures for estimating the hearing threshold level associated with noise exposure, aging and their interaction. These normative data could be integrated into the revised version of “Detectsound”.

2.3.3. Data on frequency selectivity

Frequency selectivity is one of the most important characteristics of the auditory system. It contributes to the detection of signals in noisy backgrounds and to the ability of identifying sounds from their spectral shape (Laroche et al., 1992). It is a key factor affecting masked thresholds estimation and loudness computation.

“Detectsound” was originally designed to follow the frequency selectivity model by Zwicker (Laroche et al., 1991). Zwicker et al.(1965) described frequency selectivity by critical bandwidth using narrowband maskers. More recent findings have indicated that Zwicker’s model may have some problems. Moore et al. (1996; 1997b; 1997c) argued that Zwicker’s model might be problematic methodologically. Firstly, the narrowband method it is based on may be influenced by such factors as beat detection, combination tones and off-frequency listening (detection of signal using an auditory filter or critical band that is not centred at the signal frequency). Secondly, the high-frequency side of the masking patterns can be strongly influenced by the inherent temporal fluctuations in narrowband noise maskers, especially when the bandwidth is very narrow and the fluctuations are correspondingly slow.

Furthermore, Zwicker’s model failed to consider data from subjects with hearing loss. Moore et al.(1997c) mentioned some studies that found that for hearing impaired individuals, the increase in loudness with increasing bandwidth is less than the increase occurring in normally hearing individuals. Also, Zwicker’s model does not take into account the changes in frequency selectivity associated with age. Patterson et al.(1982) found that frequency selectivity does change with age. At age 20, the critical bandwidth is approximately 11% of the centre frequency and the deteriorating rate is 2% per decade thereafter. Therefore, the frequency data for “Detectsound” needs to be updated by more recent and accurate research findings.

2.3.4. User friendliness

User friendliness was one of the primary concerns among researchers at the time of designing “Detectsound”. Ergonomists were invited to design the prototype of user interface, and the prototype was tested with four health and safety professionals, two industrial hygienists, one engineer and one audiologist. Their comments were considered in preparing the final version of the interface (Groupe d’Acoustique de l’Université de Montréal, 1992). Due to programming technology constraints at the time, the whole software is in DOS and keyboard style, which now is out of date. MS-Windows has replaced DOS to be the most popular operating system for personal computer users. Nowadays, most users are not familiar with the operations required for using the original “Detectsound”.

One aim of this research is to update the programming technology behind “Detectsound”, and to make it easier and friendlier to today’s users.

2.4 Recent advancements in estimating auditory sensitivity

2.4.1. Estimation of hearing threshold shift due to noise exposure

The effect of long-term noise exposure on hearing has been normalized by the International Standard Organization and is described by the following formulae defined in ISO 1999 (1989). If noise exposure is longer than 10 years, the median potential NIPTS values $N_{0.50}$ for both sexes is described by:

$$N_{0.50; 10 \leq \theta \leq 40} = [\mu + v \log_{10}(\theta / \theta_0)] (L_{ex, 8h} - L_0)^2 \quad (1)$$

For noise exposure less than 10 years, its effect is described by:

$$N_{0.50; < 10} = \log_{10}(\theta + 1) / \log_{10} 11 N_{0.50; = 10} \quad (2)$$

where $L_{ex, 8h}$ is the daily A-weighted sound exposure level, L_0 is a reference exposure level dependent on frequency, θ is the years of exposure ($\theta_0=1$) and μ , v are given coefficients as shown in Figure 2.6. If noise level is below L_0 at a frequency, the effect of noise exposure at this frequency is defined as 0. For impact noise, $L_{ex, 8h}$ is adjusted by adding 5dB.

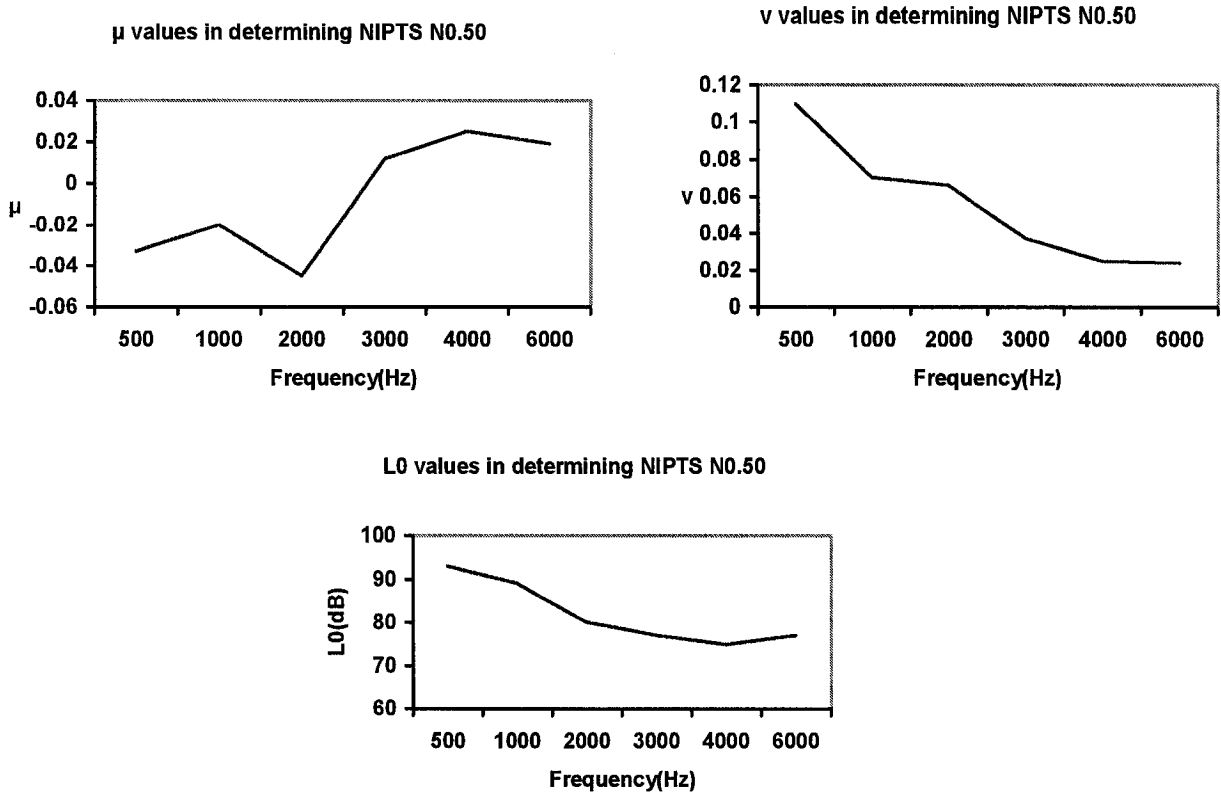


Figure 2.6: μ, v, L_0 parameters in Equation(1) (from ISO 1999, 1989)

$N_{0.50}$ denotes the median values of the NIPTS distribution. The statistical distribution of N across individuals is approximated by two separate halves from two normal (Gaussian) distributions. If we define the upper half for the fractile of the population with hearing worse than the median value $N_{0.50}$, it is characterized by the dispersion parameter d_U ; the lower half is defined for the fractile of the population with hearing better than the median, and has a smaller dispersion characterized by the parameter d_L . For a fractile of Q of the population such that $0.05 < Q < 0.50$, the NIPTS is given by the equation:

$$N_{0.05 < Q < 0.50} = N_{0.50} + kd_U \quad (3)$$

For a fractile of Q of the population such that $0.50 < Q < 0.95$, the NIPTS is given by the equation:

$$N_{0.50 < Q < 0.95} = N_{0.50} - kd_L \quad (4)$$

Values of the multiplier k are given in Figure 2.7 in intervals of 0.05 for Q .

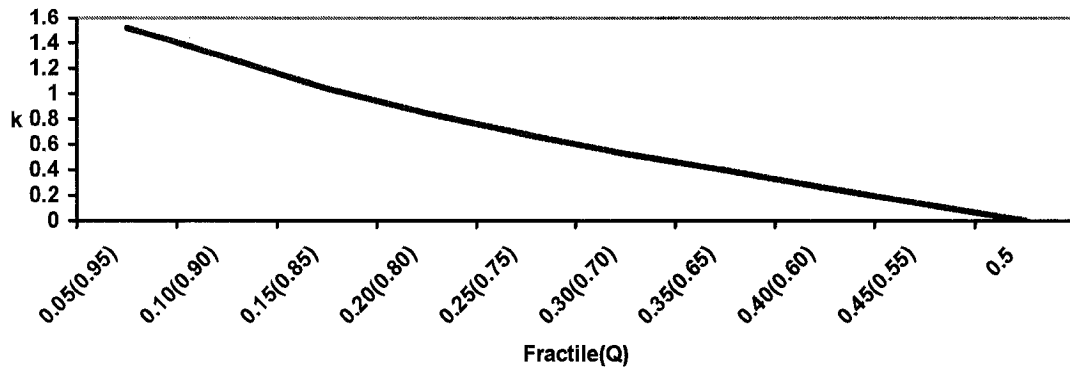


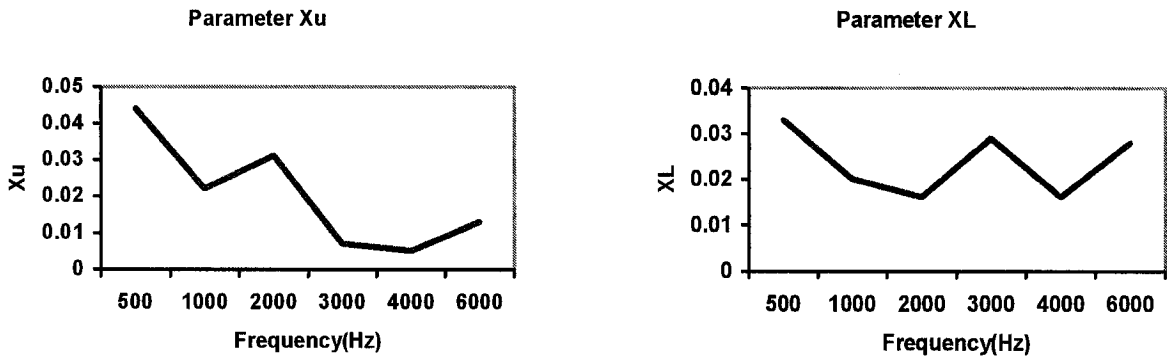
Figure 2.7: Distribution of the multiplier k in Equations (3) and (4) (from ISO 1999, 1989)

The dispersion parameters of d_U , d_L are defined by the following equations:

$$d_U = (X_U + Y_U \log_{10}(\theta/\theta_d))(L-L_d)^2 \quad (5)$$

$$d_L = (X_L + Y_L \log_{10}(\theta/\theta_d))(L-L_d)^2 \quad (6)$$

where X_U , Y_U and X_L , Y_L are constants given in Figure 2.8.



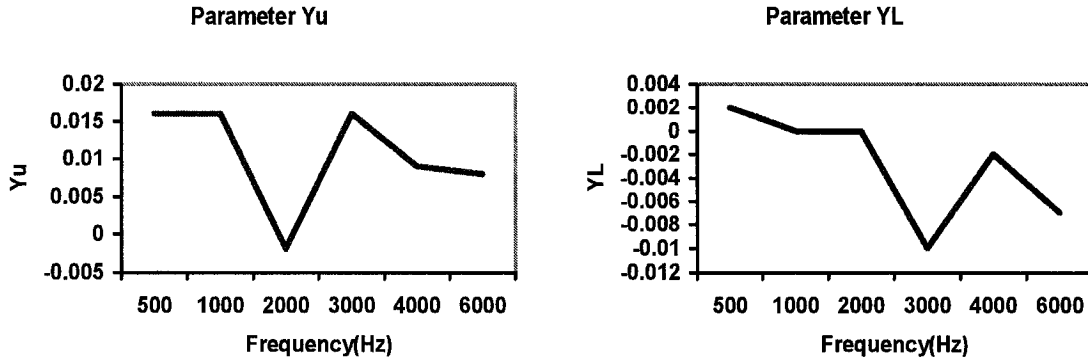


Figure 2.8: Values of the parameters X_U , Y_U and X_L , Y_L used to determine the dispersion parameters d_U and d_L characterizing the upper and lower parts of the statistical distribution of NIPTS ($N_{0.05} < N < N_{0.95}$) (from ISO1999, 1989)

2.4.2 Estimation of hearing threshold shift due to aging

Hearing threshold shifts with aging are defined by ISO 7029 (International Standard Organization, 2000). If we denote the median hearing threshold deviations for otologically normal persons of a specific age Y and sex as $H_{0.50}$, then $H_{0.50}$ will be defined by the following equation:

$$H_{0.50} = \alpha(Y-18)^2 \quad (7)$$

Values of the coefficient α for males and females are given in Figure 2.9.

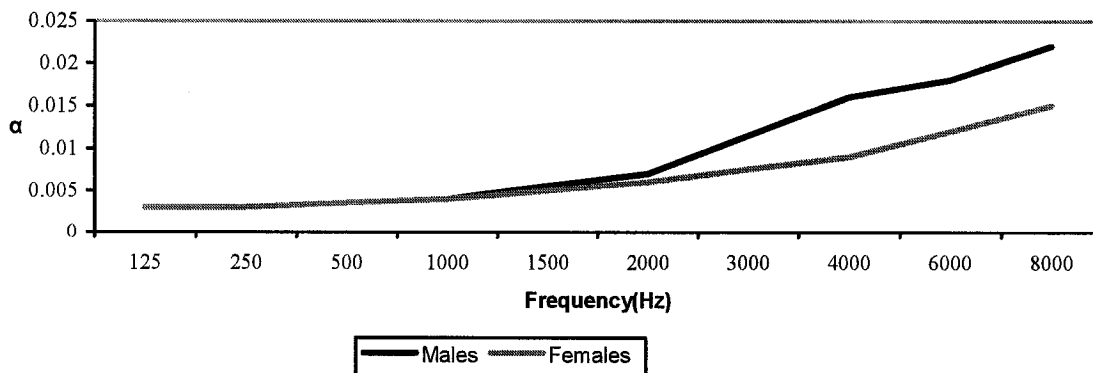


Figure 2.9: Values of the coefficient α in Equation(7) (from ISO 7029, 2000)

Similarly to NIPTS, the distribution of H around the median is approximated by separate upper and lower Gaussian halves, each with their own standard deviation s_U and s_L given by the following equations:

$$S_U = b_U + 0.445 H_{0.50} \quad (8)$$

$$S_L = b_L + 0.356 H_{0.50} \quad (9)$$

where b_U and b_L have the values given in Figure 2.10.

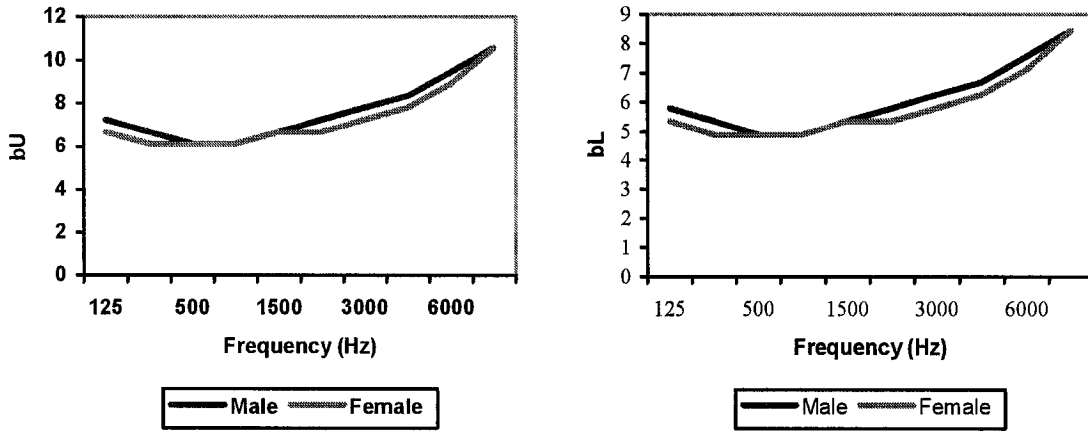


Figure 2.10: Distribution of b_U and b_L across frequencies (from ISO 7029, 2000)

The distribution with fractiles Q are given by:

$$H_{0.05 < Q < 0.50} = H_{0.50} + k s_U \quad (10)$$

$$H_{0.50 < Q < 0.95} = H_{0.50} - k s_L \quad (11)$$

where the multiplier k depends on Q as shown in Figure 2.11.

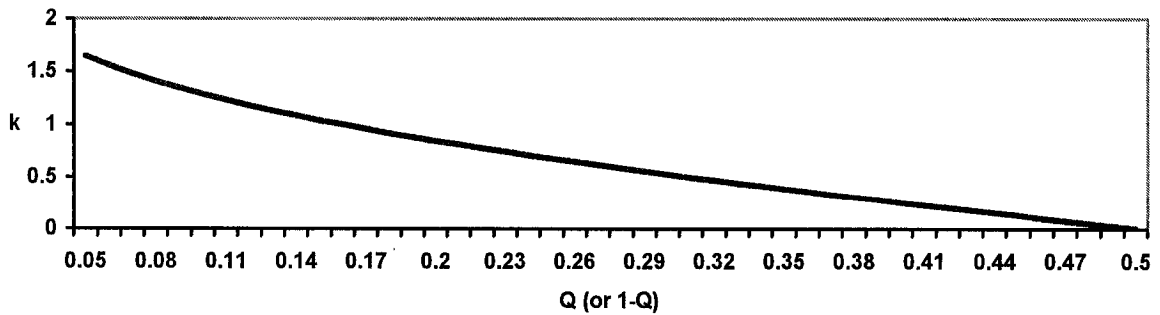


Figure 2.11: Values of the multiplier k in Equations(10) and (11) as a function of the fractile Q of the Gaussian distributions (from ISO 7029, 2000)

2.4.3. Hearing threshold level associated with noise exposure and age

The hearing threshold level H' associated with age and noise exposure is described by the following empirical formula:

$$H' = H + N - \frac{H \times N}{120} \quad (12)$$

where H is the hearing threshold level associated with age as specified in Section 2.4.2, N is the actual or potential noise-induced permanent threshold shift (NIPTS) specified in Section 2.4.1, and $H \times N$ is the interaction factor of H and N . When $H + N$ is smaller than 40dB, the term $\frac{H \times N}{120}$ has a minor effect.

The following example from Annex D of ISO 1999 (1989) shows the exact procedure for assessing the risk of noise-induced hearing impairment and age. Suppose that the target population are male, 50 years old, exposed to an average daily equivalent continuous A-weighted sound pressure level $L_{Aeq,8h} = 90$ dB for 30 years (8 hours/day, 5 days/week, 50 week/year, non-impact noise). For handicap assessment, the frequencies of 1,2 and 4kHz are normally assessed. The details are shown below for three different fractiles (0.1,0.5,0.9) of the population. The age-related hearing threshold level H for the non-noise-exposed population is calculated in accordance with Database A, Annex A.

Hearing threshold associated with age:

$$\begin{aligned} H_{0.50; 1\text{kHz}} &= 0.004 \times (50 - 18)^2 = 4 \text{ dB}; \\ H_{0.50; 2\text{kHz}} &= 0.007 \times (50 - 18)^2 = 7 \text{ dB}; \\ H_{0.50; 4\text{kHz}} &= 0.016 \times (50 - 18)^2 = 16 \text{ dB}; \\ H_{0.90; 1\text{kHz}} &= H_{0.50; 1\text{kHz}} - 1.282 \times (4.89 + 0.356 \times 4) = -4 \text{ dB}; \\ H_{0.90; 2\text{kHz}} &= H_{0.50; 2\text{kHz}} - 1.282 \times (5.78 + 0.356 \times 7) = -4 \text{ dB}; \\ H_{0.90; 4\text{kHz}} &= H_{0.50; 4\text{kHz}} - 1.282 \times (6.67 + 0.356 \times 16) = 0 \text{ dB}; \\ H_{0.10; 1\text{kHz}} &= H_{0.50; 1\text{kHz}} + 1.282 \times (6.12 + 0.445 \times 4) = 14 \text{ dB}; \\ H_{0.10; 2\text{kHz}} &= H_{0.50; 2\text{kHz}} + 1.282 \times (7.23 + 0.445 \times 7) = 21 \text{ dB}; \\ H_{0.10; 4\text{kHz}} &= H_{0.50; 4\text{kHz}} + 1.282 \times (8.34 + 0.445 \times 16) = 37 \text{ dB}; \end{aligned}$$

Noise-induced permanent threshold shift (NIPTS):

$$N_{0.50; 1\text{kHz}} = [-0.02 + 0.07 \cdot \log_{10}(30/1)](90-89)^2 = 0 \text{ dB};$$

$$\begin{aligned}
N_{0.50; 2\text{kHz}} &= [-0.045 + 0.066 * \log_{10}(30/1)](90-80)^2 = 5 \text{ dB}; \\
N_{0.50; 4\text{kHz}} &= [0.025 + 0.025 * \log_{10}(30/1)](90-75)^2 = 14 \text{ dB}; \\
N_{0.90; 1\text{kHz}} &= N_{0.50; 1\text{kHz}} - 1.282[0.020 + 0 * \log_{10}(30/1)](90-89)^2 = 0 \text{ dB}; \\
N_{0.90; 2\text{kHz}} &= N_{0.50; 2\text{kHz}} - 1.282[0.016 + 0 * \log_{10}(30/1)](90-80)^2 = 3 \text{ dB}; \\
N_{0.90; 4\text{kHz}} &= N_{0.50; 4\text{kHz}} - 1.282[0.016 - 0.002 * \log_{10}(30/1)](90-75)^2 = 10 \text{ dB}; \\
N_{0.10; 1\text{kHz}} &= N_{0.50; 1\text{kHz}} + 1.282[0.022 + 0.016 * \log_{10}(30/1)](90-89)^2 = 0 \text{ dB}; \\
N_{0.10; 2\text{kHz}} &= N_{0.50; 2\text{kHz}} + 1.282[0.031 - 0.002 * \log_{10}(30/1)](90-80)^2 = 9 \text{ dB}; \\
N_{0.10; 4\text{kHz}} &= N_{0.50; 4\text{kHz}} + 1.282[0.005 + 0.009 * \log_{10}(30/1)](90-75)^2 = 19 \text{ dB};
\end{aligned}$$

Hearing threshold level associated with age and noise:

$$\begin{aligned}
H^?_{0.50; 1\text{kHz}} &= 4 + 0 - \frac{4 \times 0}{120} = 4 \text{ dB}; \\
H^?_{0.50; 2\text{kHz}} &= 7 + 5 - \frac{7 \times 5}{120} = 12 \text{ dB}; \\
H^?_{0.50; 4\text{kHz}} &= 16 + 14 - \frac{16 \times 14}{120} = 28 \text{ dB}; \\
H^?_{0.90; 1\text{kHz}} &= -4 + 0 - \frac{-4 \times 0}{120} = -4 \text{ dB}; \\
H^?_{0.90; 2\text{kHz}} &= -4 + 3 - \frac{-4 \times 3}{120} = -1 \text{ dB}; \\
H^?_{0.90; 4\text{kHz}} &= 0 + 10 - \frac{0 \times 10}{120} = 10 \text{ dB}; \\
H^?_{0.10; 1\text{kHz}} &= 14 + 0 - \frac{14 \times 0}{120} = 14 \text{ dB}; \\
H^?_{0.10; 2\text{kHz}} &= 21 + 9 - \frac{21 \times 9}{120} = 28 \text{ dB}; \\
H^?_{0.10; 4\text{kHz}} &= 37 + 19 - \frac{37 \times 19}{120} = 50 \text{ dB};
\end{aligned}$$

2.5. Recent advancements in modeling auditory perception

2.5.1. Transmission factor in auditory system

Zwicker's loudness model (Zwicker & Sharf, 1965) had widely been acknowledged to be a fairly successful loudness model. Most recent loudness models (Moore et al., 1996, 1997; Launer, 1995; Appell, 2002) can be regarded as revised versions of Zwicker's model. Generally, this kind of loudness models consists of the following main stages:

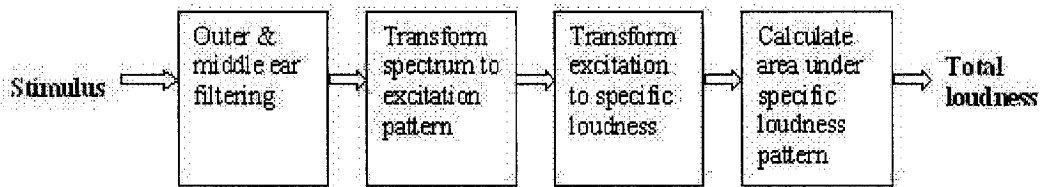


Figure 2.12: Main stages of loudness models based on Zwicker’s model

In psychophysical research, the peripheral stage of hearing is often treated as though the incoming sound is passing through a linear transmission correction followed by a bank of band pass filters, called auditory filters. Transmission factors account for the transmission of sound through the outer and middle ear. Different workers used different implementations of the transmission factor. Zwicker (Zwicker et al., 1965) assumed a linear transmission through the outer and middle ear. Above 2000Hz, this transmission function was similar in form to the absolute thresholds but inverted in shape, thus the transmission correction is done by subtracting MAF from the input sound. Below 2000Hz, he assumed that the transmission is uniform; the rise in absolute threshold with decreasing frequency reflected increased internal noise. The input sound spectrum is corrected by subtracting a constant value (MAF at 2000Hz).

More recent researchers, like Moore & Glasberg (1996), disagreed with Zwicker. They followed publications from Zwislocki (1975) and Rosowski (1991), and argued that it is unrealistic to ascribe the whole increase in absolute threshold at low frequencies to internal noise. Instead, they proposed a correction called “ELC correction”. They assumed that transmission through the outer and middle ear at frequencies below 1000Hz (for a frontally-incident sound in free-field) follows roughly the form of the equal-loudness contour (ELC) at a relatively high loudness level of about 100 phons; above 1000Hz, the transmission factor is assumed to be reflected in the shape of the absolute threshold curve. A comparison of the transmission curves by Zwicker and Moore is shown by Figure 2.13.

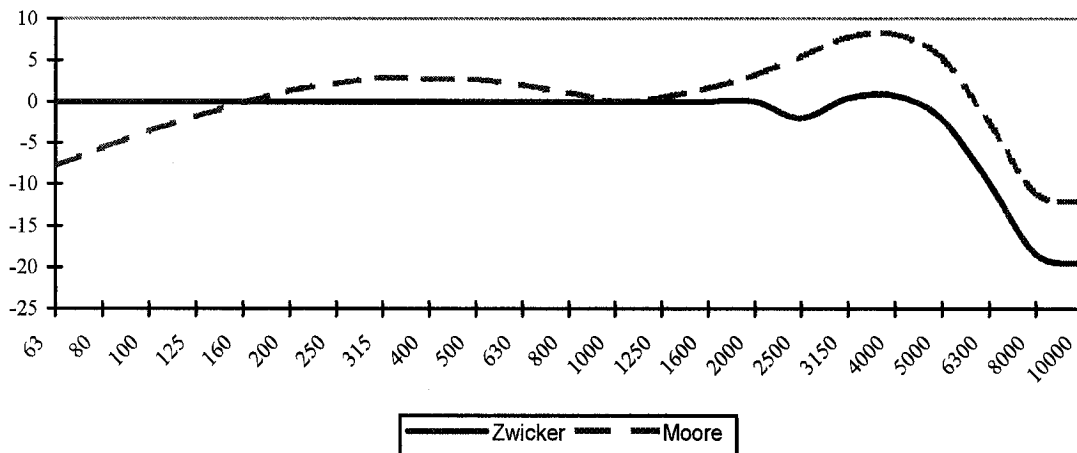


Figure 2.13: Moore's ELC correction and Zwicker's transmission correction.

2.5.2. Moore's studies on frequency selectivity

As discussed above, Moore (Moore et al, 1987) disagreed with Zwicker's narrowband noise method in studying frequency selectivity. Together with others, he proposed the using of a notched-noise method. A notched-noise is a wide band noise with a notch at a selected range of frequencies. Moore argued that this method is superior in studying frequency selectivity: the presence of background noise will mask any combination tones and reduce the benefit of off-frequency listening. Thus it is not affected by the detection of beats between the signal and masker, or by the detection of combination products produced by the interaction of the signal and masker, therefore leading to a more accurate measurement of the filter shape. When describing frequency selectivity, Moore et al. (1987) also advised to express the auditory filter bandwidth in ERB (Equivalent Rectangular Bandwidth) instead of Bark (critical bandwidth). ERB scale and Bark scale have been shown in Figure 2.5. At moderate sound levels, the auditory filter bandwidth (ERB) for normal hearing subjects is roughly described by

$$ERB = 24.7 (4.37F + 1)$$

Where ERB is the filter bandwidth in Hz, F is centre frequency in kHz. Figure 2.14 displays the relationship between auditory filter centre frequency and bandwidth (ERB).

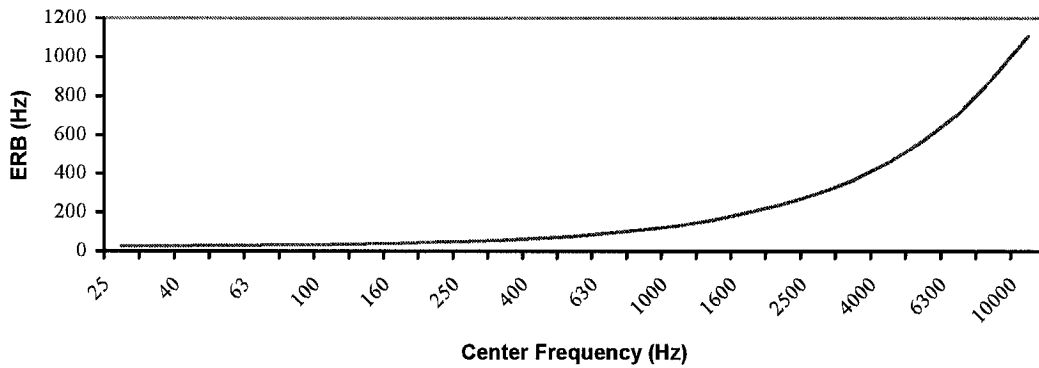


Figure 2.14: The relation between auditory filter bandwidth (ERB) and centre frequency

Shape of the auditory filter can be described by:

$$W(g) = (1+pg).exp(-pg)$$

Where $g = |f - f_0|/f_0$, $p = (4 \times f_0)/ERB$ is the slope of the filter. An example of auditory filter shape at 2 kHz (with bandwidth of 240Hz) defined by this equation is shown in Figure 2.15 (Here we assume the filter is symmetric). For comparison, ERBs for twice width (480Hz, corresponding to 55 dB HL) and 3.8 times width (912Hz, corresponding to 78 dB HL) are also displayed. These increases in width are associated with a decrease in frequency selectivity often encountered in people with sensorineural hearing loss.

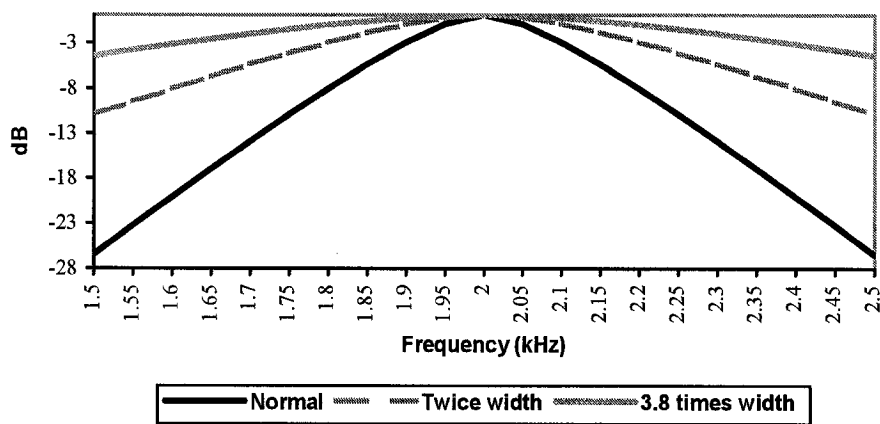


Figure 2.15: ERB broadening associated with hearing loss for 3 hypothetical subjects at frequency of 2kHz

Moore's model has similar predictability as Zwicker's model in describing frequency selectivity data for people with normal hearing. However Moore's model is more powerful at describing data for people with hearing loss (as shown in Figure 2.15). They partitioned the hearing loss into two types: the loss due to damage to outer hair cells (OHCs), and the loss due to damage to inner hair cells (IHCs). Loss of frequency selectivity is assumed to be associated with OHC loss. As suggested by Moore et al. (1997b), auditory filters do not broaden at all for hearing losses less than 22 dB; for hearing losses between 22 and 55dB HL, centre frequencies above 1 kHz, the ERB of the auditory filter is broadened by a certain factor B, which is described by

$$B = 10^{0.01757(HL_{OHC} - 22)}$$

HL_{OHC} is hearing loss level due to OHCs. Usually, it accounts for 70% of the total hearing loss (for HL_{OHC} greater than 55 dB, HL_{OHC} is defined as 55 dB). The maximum bandwidth of a broadened filter is defined as 3.8 times that of normal hearing individuals.

For frequencies below 1 kHz, cochlear hearing impairment appears to have smaller effect on the sharpness of auditory filters. Then the broadening rate for ERB can be described by

$$B = 10^{0.01757[1 - (F-1)^2 / 3.09]}$$

where F is the centre frequency in kHz and is always less than 1.

Finally, the auditory filter shape can be used to compute the masked detection threshold of a signal in noise according to the following equation,

$$P_s = K \int_0^{\infty} N_{(f)} W_{(f)} df$$

P_s is the power of the signal at threshold, K is a constant that is related to the efficiency of the detection mechanism following the auditory filter, which equals to the signal-to-masker ratio at the output of the filter required for the threshold, $N_{(f)}$ refers to the masker spectrum, and $W_{(f)}$ is the filter shape which has been introduced above and shown in Figure 2.15.

2.5.3. Models for specific loudness computation

Zwicker et al.(1965) suggested that loudness is not directly related to stimulus intensity of the coming sounds, but is related to the excitation pattern evoked by the

stimulus. They referred excitation pattern to the spread of excitation along the basilar membrane. Excitation pattern is frequency dependent and can be represented on a physiologically motivated frequency scale. Later researchers agree on this principle but describe the excitation pattern in different ways.

Zwicker et al.(1965) developed the Bark-scale, which was closely related to critical bandwidth. In their opinion, excitation pattern cannot be measured directly and has to be derived from narrowband noise masking patterns. It was assumed that excitation patterns evoked by such noises were similar in shape to the masking patterns but shifted by a few dB. The exact shift amount depends on the frequency, for the lower and middle frequencies it is 3 dB, for the higher frequencies it is 6 dB. The excitation pattern is given by adding such a shift to masked pattern. As the derivation of the excitation pattern is very cumbersome, one has to rely on a set of standard masking patterns and their derived excitation patterns published by Zwicker.

Moore (1996) advocates calculating excitation patterns directly from auditory filter shapes. The excitation pattern for a given sound is defined as the pattern of outputs from the auditory filters as a function of filter centre frequency. The auditory filter shape represents frequency selectivity at a particular centre frequency; the equivalent rectangular bandwidth (ERB) of the auditory filters can be described as

$$ERB = 24.7 (4.37F+1)$$

Where ERB is in Hz, centre frequency F in kHz.

Once the excitation patterns are known, they can be transformed to specific loudness. A basic assumption is that the specific loudness produced by a given amount excitation is proportional to the internal effect evoked by that excitation. This is described as:

$$N' = C. E^{\alpha}$$

where N' refers to specific loudness, E is excitation in power units, C and α are constants and $\alpha < 1$. However, the formulas describing this transformation differ across researchers. A set of popular models is discussed below.

Zwicker et al.(1965) advocated the formula of

$$N' = 0.08 \left(\frac{Et}{E_0} \right)^{0.23} \times \left[\left(\frac{1}{2} \frac{E}{Et} + \frac{1}{2} \right)^{0.23} - 1 \right]$$

where N' is specific loudness, E_t refers to excitation produced by an external tone at the absolute threshold, E_0 is a reference value corresponding to $I_0 = 10^{-16}$ watt/cm² and E is the excitation level.

Moore & Glasberg (1996) suggested another equation for calculating specific loudness based on their use of ERB to derive excitation level. Their formula is,

$$N'_{SIG} = 0.0806[1 - (kE_{NOISE}/E_{SIG})] \times [(E_{SIG}/E_0)^{0.2106} - (E_{THRQ}/E_0)^{0.2106}]$$

where N'_{SIG} is the specific loudness, E_{SIG} is the excitation evoked by the signal, E_{THRQ} is the excitation level at absolute threshold, E_{NOISE} denotes the excitation evoked by the noise, E_0 is the excitation produced by a sound at 0 dB SPL, k is the ratio of signal power to noise power within the ERB around the signal frequency for a signal at threshold.

Launer (1995) also suggested a way of calculation at this stage. Appell (2002) reviewed his work and express Launer's suggestion as the following:

$$N' = C \cdot \left(\frac{E_{[ELCC]}}{E_{Thq [HL]}} \right)^{\beta \cdot \alpha}$$

This is a two-component approach. $E_{Thq [HL]}$ equals the excitation at audiometric threshold

relative to average normal hearing threshold, $E_{[ELCC]}$ is the ELC corrected excitation level, α defines the slope of the loudness function and the audiometric threshold $E_{Thq [HL]}$,

which can be adjusted for an individual, and β describes the frequency dependence of the exponent. Launer's approach has its main focus on hearing impaired people; it has some difficulties in applying to normal people. For example, it cannot accurately predict normal hearing thresholds in quiet.

Appell (2002) did a comparison test among these above loudness models. The C and α parameters are adjusted, so that for all above models, a loudness of 1 sone is achieved for a 1kHz tone at the level of 40dB SPL; 2 sones is achieved when the 1 kHz tone is increased by 10dB SPL to 50 dB SPL; 4 sones is achieved when the tone is at 60 dB SPL; 8 sones is achieved when the tone is at 70 dB SPL. The required parameter adjustments for the different models are as following:

Table 2.1: A comparison between popular loudness models (from Appell, 2002)

Parameter	Zwicker	Moore	Launer
C	0.0960	0.0730	0.0401
α	0.0283	0.2159	0.2522

Appell also proposed his own model for specific loudness calculation, which can be described as:

$$N^{\prime} = \begin{cases} c \cdot \left(\left(\frac{E_{[ELCC]}}{E_{Thq[HL]}} \right)^{\beta \cdot \alpha} - (E_{MAF[ELCC]})^{\beta \cdot \alpha} \right) & \text{for } \frac{E_{[ELCC]}}{E_{Thq[HL]}} > E_{MAF[ELCC]} \\ 0 & \text{for } \frac{E_{[ELCC]}}{E_{Thq[HL]}} < E_{MAF[ELCC]} \end{cases}$$

For normal hearing, when $E_{Thq[HL]}$ and β are equal to one, it equals the formula proposed by Moore et al.(1996). The validity of this model is to be tested.

The relation between specific loudness and loudness is simple and is generally agreed by researchers. It can be either described by

$$N = \int_{z=0}^{z=24} N^{\prime} dz \quad (\text{Bark})$$

or

$$N = \int_0^{\infty} N^{\prime}_{f_{ERB}} d f_{ERB} \quad (\text{ERB})$$

Moore et al. (1996) compared their model with Zwicker's. They concluded that their model has some advantages over predicting ISO 226 (1987). Appell (2002) found that both models, Zwicker's and Moore's, could give a good prediction of the ISO226 Equal-Loudness Contours (ELC), while Launer's model shows significant deviations for low stimulus tone levels from ELC.

After a general review of specific loudness models, some specific limitations were found in integrating anyone of these models to the new “Detectsound”. First, these models are usually validated by statistical or normalized data only. For example, Moore et al. mentioned their model’s predictability over the relationship between the levels of sound and its loudness, over equal-loudness contours summarized by ISO 226, but did not mention its predictability with individual data. Therefore one has to be very cautious before applying these models to describing individual situations. Another point we have to pay attention is its deficiency in describing partial masking. For example, Moore’s model has some difficulty in describing partial masking of sounds. In a study, Moore et al. (1985) measured the loudness reduction of a sinusoidal tone produced by a noise with a spectral notch around the frequency of the tone. For normal hearing subjects, the noise produced substantial reductions in loudness of the tone. When the noise and tone were presented to an ear with cochlear hearing impairment, the noise had little effect on the loudness of the tone. The loudness reduction for normal ears was interpreted as a consequence of the noise masking part of the excitation pattern of the tone; the absence of loudness reduction in ears with cochlear loss cannot be described by both Zwicker and Moore models. A possible reason may be that they did not take into account the non-linear effects of sound suppression.

Chapter 3. Design and implementation of the new “Detectsound”

The present research aims at developing a psychoacoustical model for optimally adjusting the levels of warning signals in the workplace, taking into account the hearing status of individual workers or a given population of workers. This work is based on the original 1991 version of the “Detectsound” model (Laroche et al., 1991a) which was reviewed in Chapter 2. We will call the psychoacoustical model developed in this project new “Detectsound” or “Detectsound”-2002. The main features are:

- (1) Incorporation of specific individual’s auditory thresholds and frequency selectivity data;
- (2) Integration of normative data for estimating hearing status of specific populations based on age and noise exposure;
- (3) Integration of more accurate procedures to account for human frequency selectivity and masked threshold estimation; and
- (4) Improvement of the user interface for the implementation software tool

3.1 Algorithm of new “Detectsound”

The main algorithm behind original “Detectsound” was based on the loudness model by Zwicker et al. (1965). Recently, this model has been questioned on the methodological aspects that possibly leading to estimation errors (Moore et al., 1996). Several other loudness models (Moore et al., 1996; Launer, 1995; Appell, 2002) that represent revisions or developments of Zwicker’s model have been reviewed in Chapter 2. Among those, only Moore’s model has been proved to give good predictability, but still may be problematic in some aspects, such as describing individual data and partial masking.

Therefore, we decided to employ a different algorithm: direct estimation of masked thresholds. Masked thresholds here refer to the lowest sound pressure level of

warning signals necessary to detect them when in the presence of different background noises that are found in a noisy industrial environment. The formula introduced by Moore et al. (1987) is:

$$P_s = K \int_0^{\infty} N(f)W(f)df \quad (13)$$

where P_s is the power of the signal at the threshold, $N(f)$ is the masker spectrum, $W(f)$ is the auditory filter shape, and K is a detection efficiency constant. The computation of masked thresholds will give us the level of warning signals that are just detectable under background noises in workplace. The characteristics of the individual workers or population of workers is accounted for by the parameters $W(f)$ and K , which can be either measured or estimated. Equation 13 must be estimated over a range of frequencies covering the frequency components of industrial warning devices (typically from 250 to 3000Hz). The optimal level of each warning signal is then set at a predetermined amount over the masked thresholds for each frequency component.

This new algorithm will be beneficial for the following reasons. Firstly, it avoids the errors resulted from loudness estimation. Secondly, it facilitates the evaluation for multiple signals. The original 1991 version of “Detectsound” evaluates the efficiency of a warning signal by comparing the loudness of the signal in presence of background noise. Therefore, each new signal has to be evaluated by a separate computing process. If the user intends to evaluate several signals, he has to run the comparison process as many times as the number of signals. In the new “Detectsound”, the range of levels of efficient warning signals for the target population (or specific individual) is directly given after one analysis process. This level depends on the background noise and the hearing status of the target individual (or population) and is independent of any signals. Thirdly, with the help of a tool developed in our lab for estimating filter shape $W(f)$, it is possible to make better use of the accurate data describing frequency selectivity (for a specific individual or certain populations).

Specifically, the implementation of the new psychoacoustical model can be described by the following flow chart (Figure 3.1). As we can see, the whole process starts by defining the required parameters for the computations. These include: background noise level (1/3 Octave, dB SPL), frequency selectivity (ERB in Hz;

measured or estimated according to normative data) and absolute hearing threshold (pure tone, dB HL) for an individual worker or a specific population. Hearing protector attenuation (dB) and warning signal (dB SPL) can also be defined. Masked thresholds are then estimated based on background noise, frequency selectivity and hearing protector (if worn). The design window is determined by such factors as masked threshold, absolute threshold and protector (if worn). The evaluation result for the warning signal and design window can be displayed graphically or in text format.

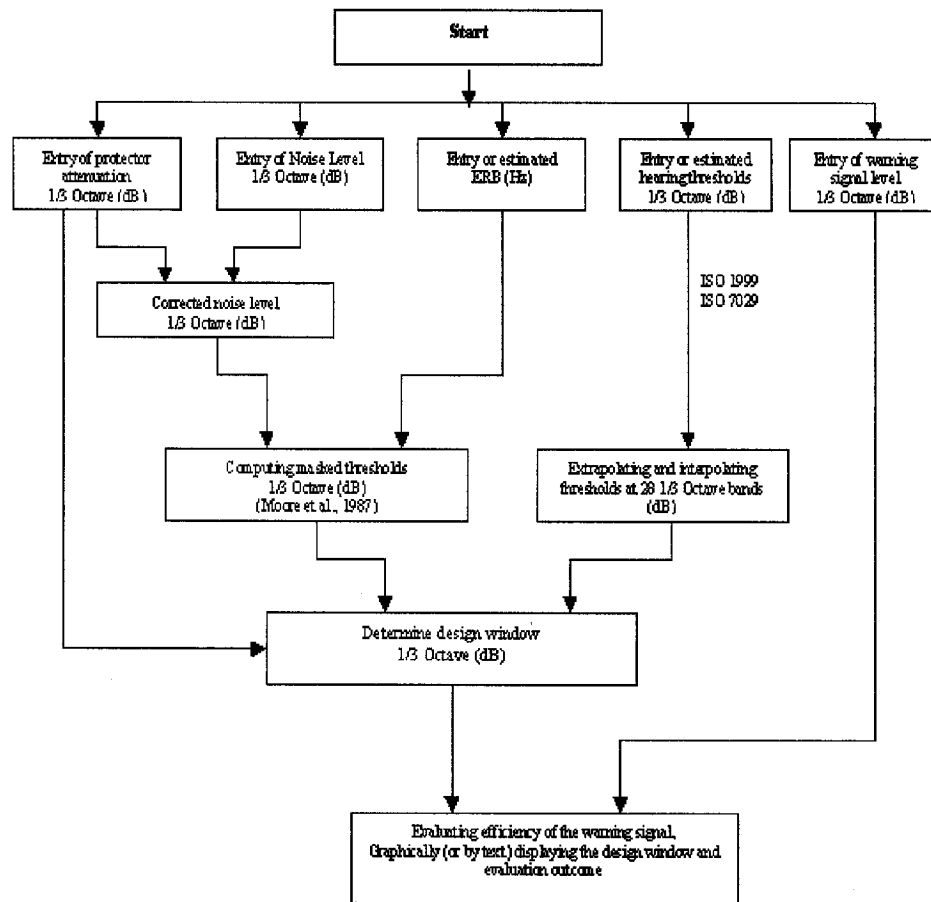


Figure 3.1: Flow chart of new “Detectsound”

A software tool reflecting the implementation of the newly developed psychoacoustical model has been completed. In the remaining part of this chapter, we will explore several aspects of this model and introduce the graphic interfaces of the software tool associated with each step of the model.

3.2. Entry of parameters

3.2.1 Entry of background noise spectrum

Like in the original “Detectsound”, the background noise is measured and described by sound pressure levels at 28 one-third-octave bands from 25 to 12,500Hz. In the workplace, the noise is normally free field. But in some cases (like laboratory validation studies), the noise is delivered by earphones. This factor has been taken into consideration in new “Detectsound”. A conversion procedure between these two types of noise presentation has been set up within the new model based on the description of ANSI S3.6 (1996). The related ANSI data is shown in Figure 3.2, and allows to convert earphone coupler noise into a free field equivalent noise and vice versa.

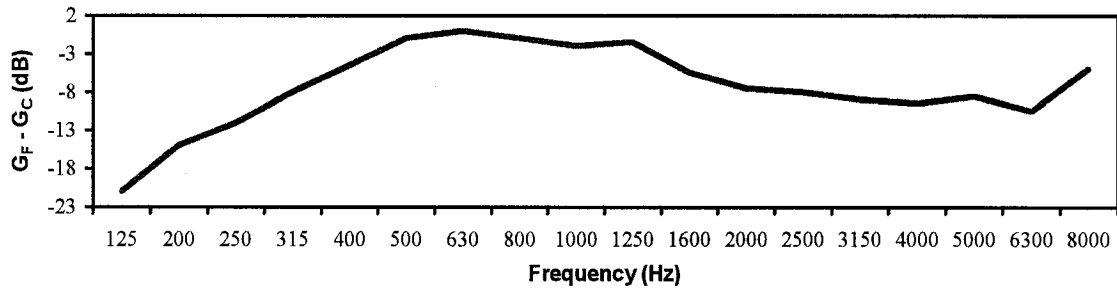


Figure 3.2: Difference between free-field equivalent sensitivity level G_F and the headphone (TDH 50) coupler level G_C (ANSI S3.6, 1996)

The software interface for the entry of noise levels (dB SPL) is shown Figure 3.3.

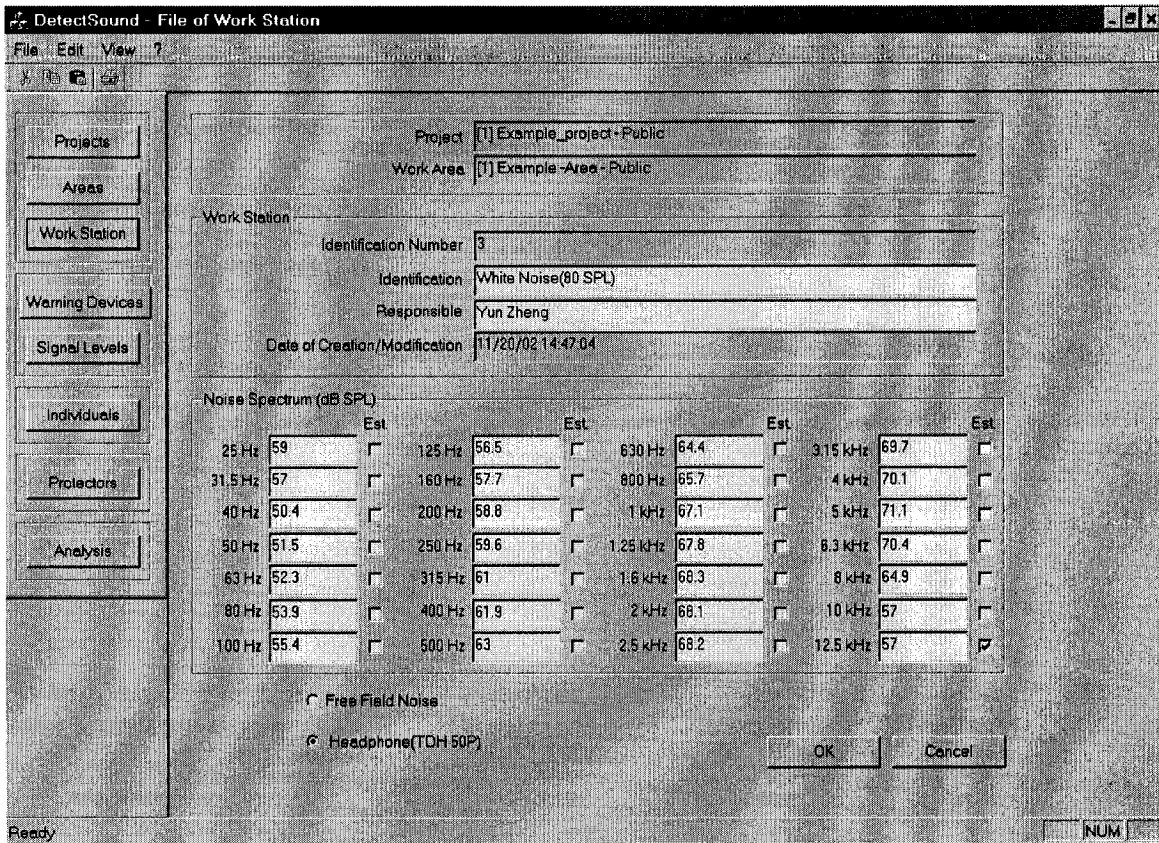


Figure 3.3: Interface for the entry of noise spectrum in “Detectsound” software in 1/3-octave bands and presentation mode (Free field or headphone)

3.2.2. Entry of hearing protector attenuation

Wearing hearing protectors is a common practice in many noisy workplaces. Protectors may attenuate the noise level, and may also affect worker’s perception for warning signals used in workplaces. This has been taken into consideration in new “Detectsound”. The attenuation values (in dB) of the protector at 63, 125, 250, 500, 1000, 2000, 4000, 8000Hz are required to be entered at this stage. The software interface is presented in Figure 3.4. The entered hearing protector information will be kept in a database and available to all “Detectsound” users.

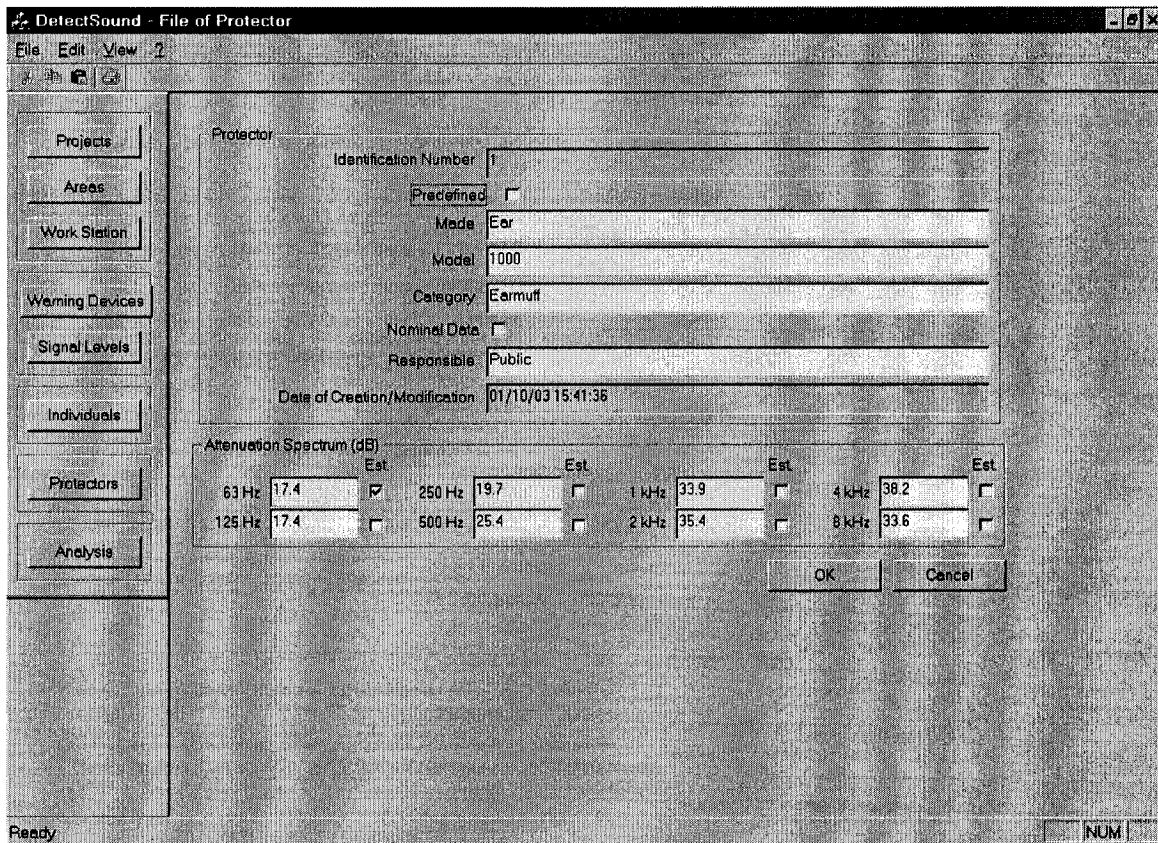


Figure 3.4: Interface for the entry of hearing protector attenuation data

3.2.3. Entry of absolute thresholds and ERB data

3.2.3.a. For a specific individual

Measured absolute thresholds of the target individual at 125, 250, 500, 1k, 2k, 3k, 4k, 6k, 8kHz are required to be entered at this stage (see Figure 3.5).

Entry of auditory filter bandwidths at 250, 500, 1k, 2k, 3k, 4kHz are also required. They are specified in terms of the equivalent-rectangular bandwidths (ERB). If measured ERB data are not available, the user is provided with an alternative way of statistically estimating these values from the absolute thresholds. The estimation procedure is based on normative ERB data collected in an ongoing research studies in our laboratory. Six young normal hearing subjects from a total of 20 have been tested so far. Based on these data, the filter bandwidths used in the new “Detectsound” are 70, 94, 164, 346, 485 and 702Hz for centre frequencies of 250, 500, 1k, 2k, 3k, 4kHz respectively (See Table 3.1).

If the ERB values are measured, no correction will be necessary. If ERB values are estimated, a set of corrections reflecting the increasing width of ERB associated with hearing loss will be done. Following the original “Detectsound”, the ERB is assumed to be equal to the normative data for absolute thresholds below 25 dB HL. For absolute thresholds above 25dB HL, the filter widths increase systematically. The relationship between filter widths and hearing sensitivity loss is approximated by a linear regression with slope varying with the centre frequency of the filter. At 250, 500, 1000Hz, the broadening rate is 7.4Hz/dB; at 2000Hz, the broadening rate is 36.7Hz/dB; at 3000, 4000Hz, the broadening rate equals to 66Hz/dB. The normative ERB values are 132,142,217,505,745, and 837 respectively (See Table 3.1). The relative broadening rates in original “Detectsound” are 7.4/132(5.6%), 7.4/142(5.2%), 7.4/217(3.4%), 36.7/505(7.3%), 66.0/745(8.9%), and 66.0/837(7.9%) at centre frequencies of 250, 500, 1k, 2k, 3k, and 4k respectively for each dB above 25 dB HL. In new “Detectsound”, we changed the normative ERB values on the basis of a recent and ongoing laboratory study, but the relative broadening rates are kept unchanged (See Table 3.1). The relationship between ERB broadening and hearing sensitivity loss will be further studied in a separate validation study with 20 hearing-impaired subjects.

Table 3.1: Normative data for original and new “Detectsound”. The relative ERB broadening rate is the percentage of broadening of auditory filter bandwidth per dB of hearing loss above 25dB HL.

Centre frequency (Hz)	ERB (Hz) Original “Detectsound”	ERB (Hz) New “Detectsound”	Relative broadening rate (% / dB)
250	132	70	5.6
500	142	94	5.2
1000	217	164	3.4
2000	505	346	7.3
3000	745	485	8.9
4000	837	702	7.9

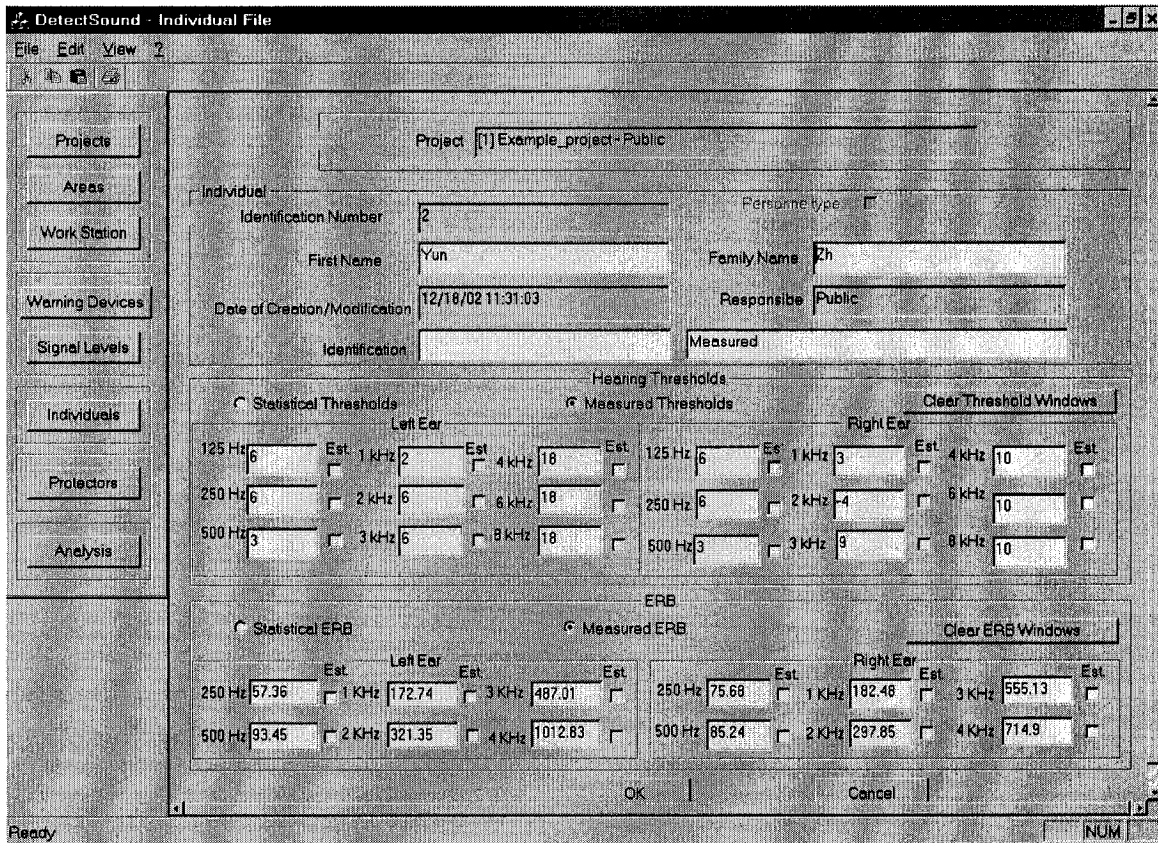


Figure 3.5: Interface for entering absolute hearing thresholds and ERB data

3.2.3.b. For a target population

For a population, the hearing status can be described by the group average of measured absolute hearing thresholds and ERBs. If those data are not available, statistical estimation of the absolute hearing thresholds based on ISO 1999/ ISO 7029 and incorporated normative data can be made according to such parameters as age, sex, years of noise exposure, noise level, noise type (impact noise or not), and fractile or percentile level. The estimation process is illustrated in Section 5.3. When absolute hearing thresholds are statistically estimated, the ERB widths are also statistically estimated based on the procedure described in Section 3.2.3.a.

3.2.4. Entry of warning signal spectrum

The warning signals can be described over 28 one-third-octave band levels from 25 to 12500Hz. The signal levels have no impact on the estimation of masked thresholds for individuals or a target population. However, the efficiency of warning signals for

specific individual or target population will be evaluated at the last stage of the process and this requires knowledge of their levels in the workplace. For a given warning signal, the frequency components falling within the design window are highlighted by different colours (See Section 3.4).

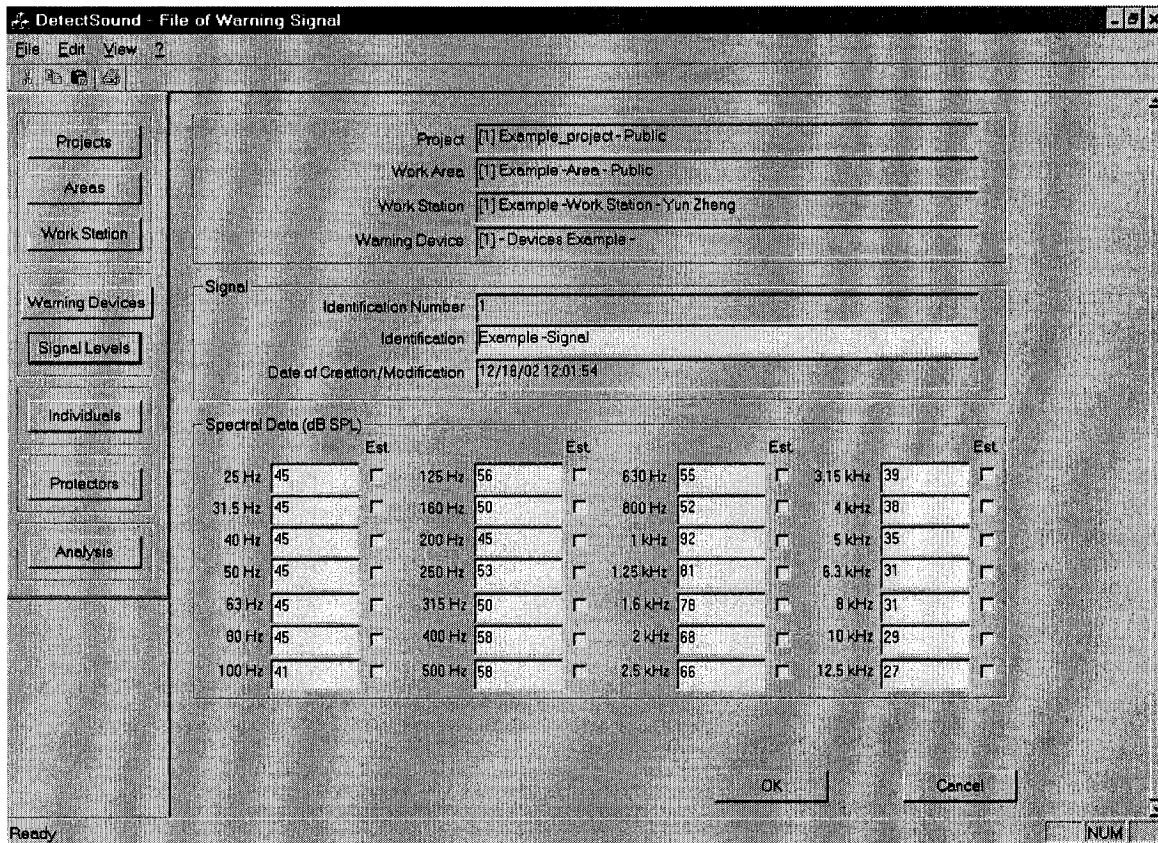


Figure 3.6: Interface for the entry of warning signal spectrum

3.3. Computation of masked thresholds

Masked thresholds are computed based on the principle proposed by Moore et al. (1987) and introduced in Section 3.1. The computation requires knowledge of the environmental characteristics (workplace noise spectrum), the hearing status of the target individual or population (absolute hearing threshold, frequency selectivity parameters), and the attenuation of hearing protectors if worn (see Figure 3.7). A series of extrapolations, interpolations and corrections are made to transform noise data to the internal ear where computation takes place. The internal masked thresholds are then transformed back to the free field, and are compared to the free-field equivalent absolute

hearing thresholds to determine the design window for the adjustment of the warning signal frequency components. The whole process of computing and using absolute and masked thresholds in “Detectsound” are described in more detail below (See Figure 3.7).

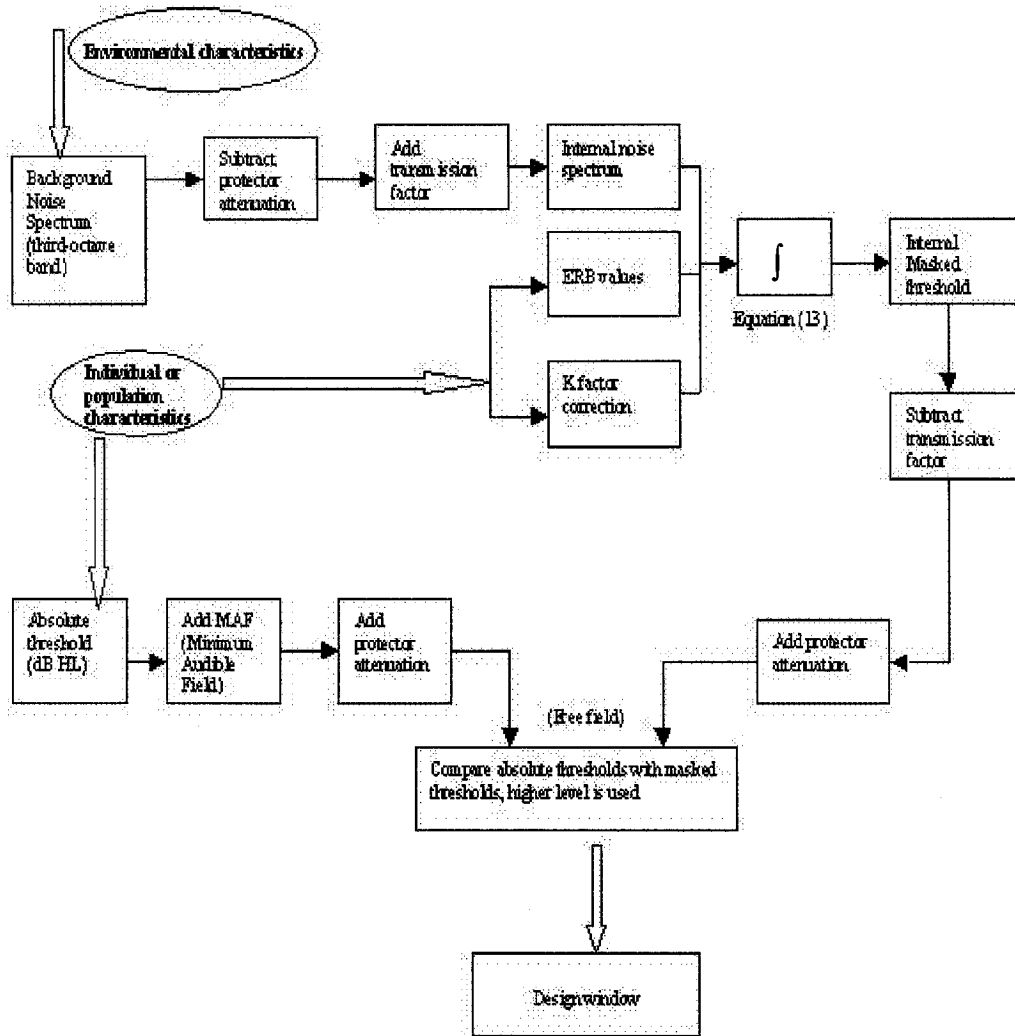


Figure 3.7: The process of computing free field equivalent absolute and masked thresholds for determining the design window of warning signals.

3.3.1. Hearing protector attenuation corrections

The attenuation (dB) of hearing protectors is typically specified at 8 octave band frequencies of 63, 125, 250, 500, 1k, 2k, 4k, 8kHz, a series of extrapolations and interpolations are needed to estimate attenuation values at 28 one-third-octave bands from 25 to 12500Hz.

For frequencies below 63Hz, the attenuation levels are assumed to be the same as the attenuation at 63Hz. For frequencies above 8000Hz, the attenuation levels are assumed to be the same as the attenuation at 8000Hz. A cubic spline interpolation method is used to derive the attenuation values over the 28 one-third-octave bands. This method allows, by using third-degree polynomials, the estimation of functions relating attenuation values at adjoining frequencies. If no protectors are worn, the attenuation levels at the 28 one-third-octave bands are defined to be 0dB.

Once all the attenuation values for the 28 one-third-octave band frequencies are obtained, the noise reduction effect of wearing hearing protectors can be accounted for by subtracting the attenuation levels (dB) from the free field background noise spectrum in the workplace (Section 3.2.1). This reflects the noise reaching the outer ear.

3.3.2 Transmission factor corrections

The next stage regards the estimation of the background noise sound pressure levels reaching the internal ear. The transmission factor considered here accounts for the transmission of the sound through the outer and middle ear.

The original version of “Detectsound” (Laroche et al., 1991) followed the general framework of Zwicker. Below 1000Hz, the hearing thresholds are assumed to be attributed to the internal noise only; no transmission correction is needed. At 1000Hz, the transmission factor is set to be 0. Above 1000Hz, transmission factor varies as a function of frequency, thus a certain transmission correction is needed. The whole process is quite cumbersome and involving a complicated low frequency correction dependent on the noise level.

In the new “Detectsound”, a more concise correction process is used in a similar manner as the “ELC correction” of Moore (Moore et al., 1996), but applied over all frequencies. The transmission factor is described by:

$$TRANS(f) = 100 - ELC(f)$$

where $TRANS(f)$ is the transmission factor and $ELC(f)$ represents the 100-phon equal-loudness contour from ISO 226 (1987). In other words, the transmission correction follows the inverted 100-phon ELC curve. The constant 100 is used to normalize the

transmission to 0dB at 1 kHz. The attained sound levels at the inner ear are then given by adding the transmission factor to the background noise spectrum reaching the outer ear (after hearing protector correction). The transmission factors are shown in Figure 3.8. For comparison, the correction adopted by Moore (1996) is also shown in the graph.

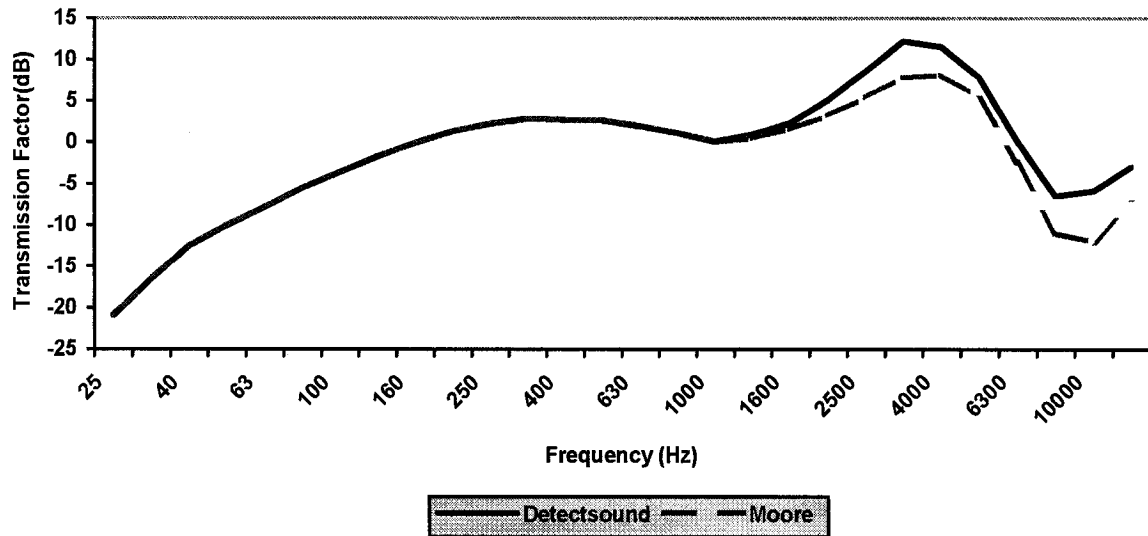


Figure 3.8: Transmission curve adopted in the new “Detectsound”. For comparison, the ELC-based correction proposed by Moore is also shown. For frequencies not exceeding 1kHz, the transmission factors in the two studies are exactly the same. Some differences appear at frequencies above 1 kHz; new “Detectsound” follows the inverted ELC curve, whereas Moore follows the inverted MAF curve.

3.3.3 Computing masked thresholds

3.3.3.a. Mathematical framework

Once the noise spectrum level reaching the inner ear and the hearing status of the target individual or population are known, the masked thresholds can be computed. As we mentioned before, the frequency selectivity model proposed by Moore et al. (1987) is adopted here. For each one-third octave band centre frequency from 125 to 3150Hz, the masked threshold P_s is computed from the noise power spectrum density $N(f)$ using:

$$P_s = K \int_0^{\infty} N(f) W(f) df$$

where $W(f)$ is the auditory filter shape and K is the efficiency factor. The noise power spectrum level $N(f)$ can be computed at each centre frequency from the one-third-octave band noise level (SPL_{dB}) using:

$$N(f)_{(dB/Hz)} = SPL_{dB} - 10 \log_{10}(0.232f_c)$$

where f_c is centre frequency within the one-third-octave band. A cubic spline is used to obtain $N(f)$ between centre frequencies. The computation of auditory shape $W(f)$ has been introduced in 2.5.2. The integral area is arbitrarily defined as $f_c \pm 2*ERB$. If $f_c - 2*ERB$ is less than 0, it is defined to be 0; if $f_c + 2*ERB$ is greater than 12500Hz, then it is defined to be 12500Hz.

As only ERB values for frequencies at 250, 500, 1k, 2k, 3k, 4kHz are available, the cubic spline interpolation method is used again to determine ERBs for frequencies range from 125 to 3150Hz (ERB at 125Hz copied the value of 250Hz). The final outcome of $P_s(f)$ is expressed in dB. We only consider the 15 one-third-octave bands from 125 to 3150Hz; therefore only masked thresholds for these frequencies are computed. These values are used to determine the warning signal design window at a later stage.

3.3.3.b. Choosing the target ear(s)

There can be wide differences in hearing status (absolute thresholds and frequency selectivity) between the two ears for a human subject, especially in case of asymmetric hearing losses. Even for normal hearing individuals, there will be small variations between the two ears. Figure 3.9 shows an example.

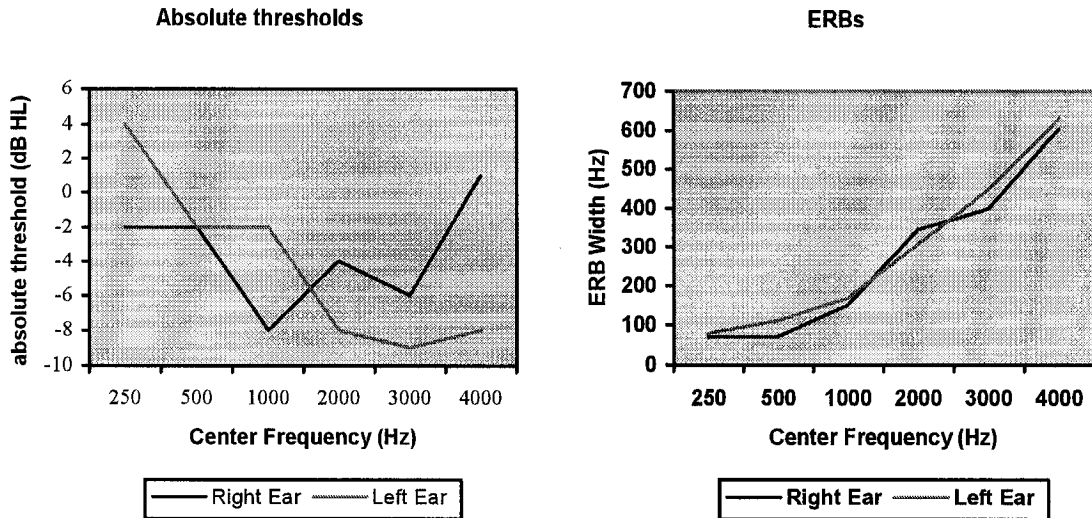


Figure 3.9: Example of hearing status difference between the two ears of a subject with normal hearing. Small differences exist in both absolute hearing sensitivity and frequency selectivity.

These variations across left and right ears indicate that masked thresholds may not be identical in each ear. Therefore, an option is made for users to choose the target ear. The user interface is as shown by Figure 3.10. If the user chooses the best ear of an individual (or target population), then the absolute hearing thresholds and ERBs for the best ear will be used for the computation of masked thresholds. The best ear is defined as the ear with the smallest arithmetical total for thresholds at 9 frequencies, left or right. If user chooses the worst ear, then the absolute thresholds and ERBs of the worst ear will be used. Users can also choose to use both ears, and then masked thresholds for both ears will be computed separately. The two masked thresholds are compared across all one-third-octave centre frequencies range from 125 to 3150Hz. The one with lower masked threshold will be chosen out to compute the design window at that frequency (There is only one exception: if the chosen value is smaller than absolute threshold at this frequency, then absolute threshold will be chosen).

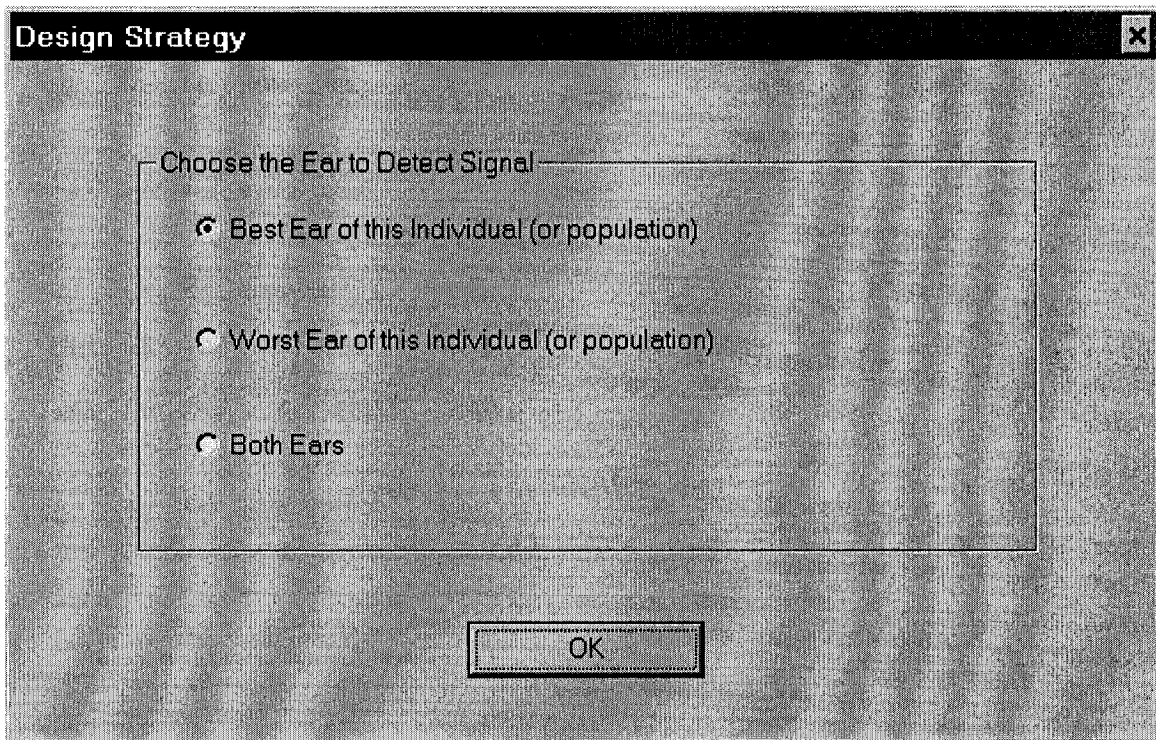


Figure 3.10: Interface for choosing target perception ear

3.3.3.c. “Detection efficiency” parameter K

As reflected in Equation(13), K is a constant for each auditory filter centre frequency. Its exact value varies on such factors as subject, the signal duration, the psychophysical method used, and the definition of threshold (Moore et al., 1996). The values that were derived from the analysis of a large body of data obtained with the notched-noise method are shown in Figure 3.11.

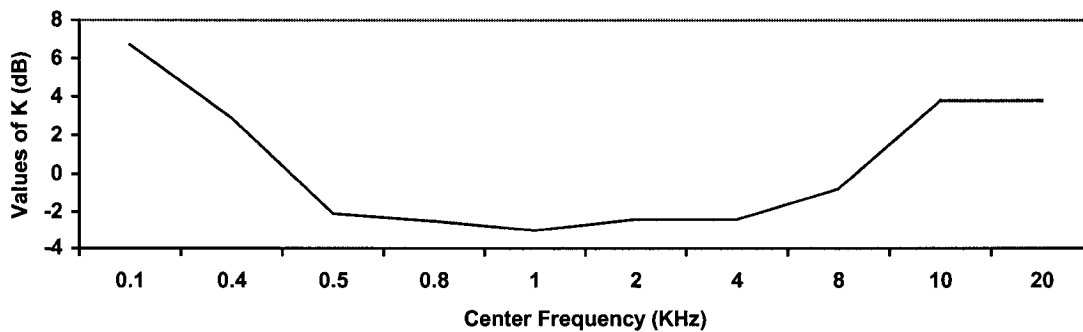


Figure 3.11: Values of parameter K at selected centre frequencies (from Moore, 1996).

K values are also taken into consideration in the new “Detectsound”. Values from Moore (1996) are used as default. If K values for specific individuals or target population are known or measured, they can be entered at runtime. The user interface is shown in Figure 3.12. A linear interpolation is used to obtain K values at frequencies between the default frequencies.

Frequency	K Value
100Hz	6.7
250Hz	4.8
400Hz	2.9
500Hz	-2.1
800Hz	-2.5
1KHz	-3
2.0KHz	-2.4
3.0KHz	-2.4
4.0KHz	-2.4
8.0KHz	-0.8
10.0KHz	3.8
20.0KHz	3.8

Figure 3.12: Interface for entering K parameter correction

3.4 Design window and analysis results

By definition, the design window is the range of sound levels that effective warning signals should fall into. It is determined from the absolute hearing thresholds of a specific individual (or target population) and the computed masked thresholds.

First, absolute thresholds at 9 frequencies are splined into 28 one-third-octave band centre frequencies from 25 to 12500Hz and transformed to the free field (Figure 3.7). Absolute threshold levels at frequencies from 125 to 3150Hz are compared with the computed masked thresholds $P_s(f)$ at the same frequencies from Section 3.3 (after correction back to free field – see Figure 3.7). The higher level (absolute vs. masked) at

each frequency is taken as the base level for the design window at that frequency. Thus, for each analysis process, there are 15 base levels for the design window.

As in the original “Detectsound” (Laroche et al., 1991), the lower boundary of the design window is determined by adding 12dB to the base levels. Whenever the produced level is above 105dB SPL, then 105 dB SPL is chosen (105dB SPL has been chosen as the maximum level in order to limit the risk of damage to hearing). The upper boundary of design window is 13dB above the lower boundary. Again, whenever a level exceeds 105dB SPL, 105dB SPL is chosen to prevent over loud warning sounds.

The design window is based on the “best” or “worst” ear as chosen in Section 3.3.3.b. If “both ears” is selected, then the lowest base level among the left and right ear is selected frequency by frequency to calculate the design window. The final design window will be displayed graphically by default (Figure 3.13). Users can also choose to display analysis information in text form (Figure 3.14). When it is graphically displayed, design window, warning signal spectrum, background noise level and a summary of analysis conditions are also displayed in the graph.

In Figure 3.13, the bright yellow area represents the design window (optimal range of warning signals). Background noise level is reflected by the blue curve. The warning signal to be analyzed is described by the line frequency spectrum. Warning signal frequencies may be highlighted by different colors. The signal frequency components falling into the design window (optimal) are displayed in green, the overly loud signal components are displayed in red, and the ineffective or too weak signal components are displayed in grey.

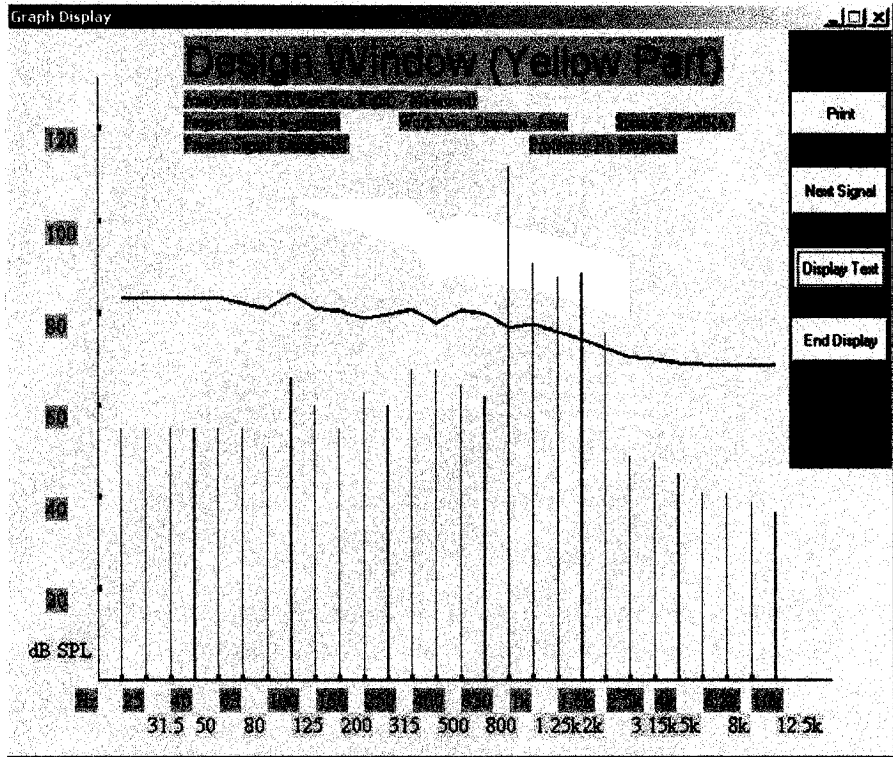


Figure 3.13: Graphical display of analysis result.

Display Text

Analysis Id: 200(Best Ear, Right) - Measured
 Project: Example_project
 Work Area: Example -Area
 Station: 87.2dB(A)
 Present Signal: Example[1]
 Protector: No Protector

Frequencies (Hz)	Noise (dB)	Design Window (dB)		Warning Signal (dB)
25.0	83.1			55.0
31.5	83.1			55.0
40.0	83.1			55.0
50.0	83.1			55.0
63.0	83.1			55.0
80.0	81.8			55.0
100.0	80.7			51.0
125.0	83.9	104.5	105.0	66.0
160.0	80.7	102.2	105.0	60.0
200.0	80.3	99.5	105.0	55.0
250.0	78.6	97.0	105.0	63.0
315.0	79.5	95.6	105.0	60.0
400.0	80.5	94.3	105.0	68.0
500.0	77.6	86.7	99.7	68.0
630.0	80.4	88.3	101.3	65.0
800.0	79.6	88.0	101.0	62.0
1000.0	76.7	85.4	98.4	112.0
1250.0	77.4	85.1	98.1	91.0
1600.0	75.8	83.6	96.6	88.0
2000.0	74.0	81.6	94.6	89.0
2500.0	72.1	80.2	93.2	76.0
3150.0	70.2	78.8	91.8	49.0
4000.0	69.8			49.0

Control Panel: Print, Save To, Destination Drive, Destination Folder, File Name, AnalysisResult.txt, Back to Graph

Figure 3.14: Displays analysis result in text form

Details of the analysis are clearly listed together. Invalid and valid frequencies are displayed in different colours: blue (too low), green (optimal) and red (too high) to facilitate easier recognition.

3.5. Discussion: Further improvement in estimating auditory filters

This chapter described the structure of the new “Detectsound”, including the computation process and the interfaces for the entry of data and view the results. A range of options is now available to the users to specify the hearing status of the target worker. When measured, absolute hearing thresholds and the auditory filter bandwidths (ERBs) are directly used to achieve an individualized solution for warning signal perception.

Additional work may be necessary in the future to refine the methods to statistically estimate the ERB values. Some studies have been done on the relationship between the decrease of frequency selectivity and loss of hearing sensitivity (Laroche et al., 1992; Moore & Glasberg, 1997). Based on data collected with 22 workers having different degrees of hearing loss, Laroche et al. (1992) found out that “above a certain degree of hearing loss, which seems to be around 30dB HL, frequency selectivity tends to decrease linearly with increase in loss of sensitivity.” However, they found that “even when the degree of hearing loss is similar, there is a wide variation among subjects in auditory filter bandwidth”. Therefore, they concluded that based on the data collected in their study, “it is not possible to adequately predict the auditory filter bandwidth of an individual from hearing threshold levels”. The authors also suggested the reason might be the variety of causes of hearing loss.

Moore and Glasberg (1997) seemed to be more successful in describing relationship between the auditory filter bandwidth and hearing threshold levels (see Section 2.5.2). Their predictions are based on the relationship between the frequency selectivity and the hearing loss due to the inner ear damage, which excluded the hearing loss due to outer and middle ear damage. It was said that their “...predictions fit the empirical data reasonably well” (Moore & Glasberg, 1997).

Presently, the broadening rates in the new “Detectsound” are inherited from the original “Detectsound”, which is different from the work of Moore and Glasberg (1997). Figure 3.15 shows the difference between the auditory filter broadening rates adopted by

new “Detectsound” and the ones computed from Moore et al. The assumed hearing loss is 55dB HL across the frequencies of 250, 500, 1000, 2000, 3000 and 4000Hz, and 70% of the hearing loss is attributed to damage to the outer hair cells (OHC). As we can see, considerable difference exists between the work of two groups of researchers.

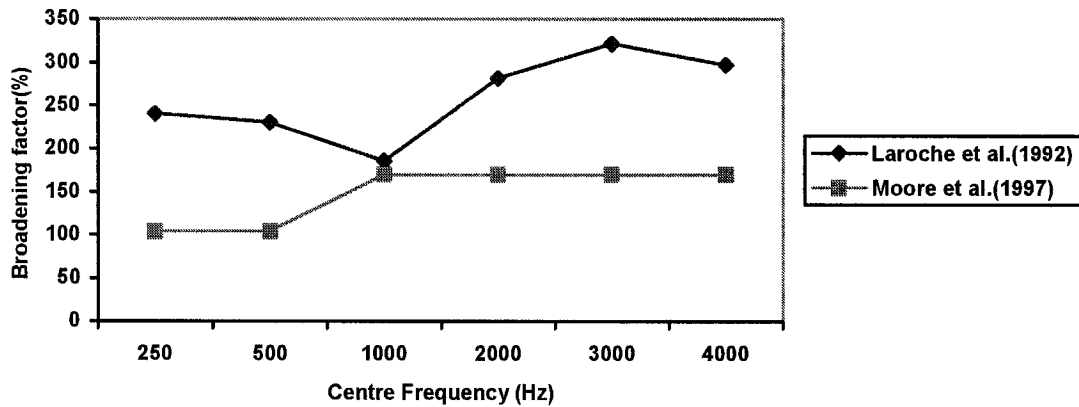


Figure 3.15: Auditory filter broadening factors from different researchers. 100% corresponds to normal-hearing auditory filter bandwidth.

Some improvements may be necessary in the future. The present broadening rates for “Detectsound” are based on the relationship between the auditory filter bandwidth and the hearing sensitivity loss as reflected by air conduction thresholds, which had been proved to have poor predictability for auditory filter bandwidth (Laroche et al., 1992). Moore’s success in using relationship between auditory filter bandwidth and hearing loss due to inner ear may have provided some helpful hints for “Detectsound”: auditory filter bandwidth may be better predicted from hearing loss due to inner ear. However, Moore’s approach relies on the knowledge of the proportion of hearing loss due to outer hair cells vs. inner hair cells. There are no clinical methods presently available to measure this parameter.

A possible alternative is to incorporate the bone conduction hearing thresholds in “Detectsound”. An increase in air conduction hearing thresholds may reflect damage to middle ear and/or inner ear. However, the increase in bone conduction hearing thresholds is considered to be directly related to damage in the inner ear. Auditory filter bandwidth

may be better predicted from the hearing loss reflected by bone conduction hearing thresholds.

Chapter 4 Validation of the new “Detectsound” model

In this Chapter, the predictions from the new “Detectsound” are examined with both individual data and group average data. As introduced in the previous chapter, “Detectsound” has been developed to predict an individual’s (or a population’s) capability of detecting warning signals in noisy worksites. The prediction is mainly based on masked thresholds derived from the hearing status (absolute thresholds, frequency selectivity) and the background noise. The design window for warning signals is actually from 12 dB to 25 dB above masked thresholds.

4.1 Validation experiment

In a separate and ongoing research project in the Audiology Research Laboratory, data are being collected on frequency selectivity for two groups of subjects: 20 individuals with normal hearing thresholds and 20 individuals with hearing loss. For each subject, auditory filter parameters (ERB, K, etc.) are derived at 6 centre frequencies from 250Hz to 4000Hz. The derivation of each auditory filter requires the measurement of six masked thresholds using notched white noise maskers. The procedure is based on Héту and Tran Quoc (1992), but the noise maskers have been regenerated to provide a better definition of the notches, and is automated using a software called SHAPE. Once completed, the results could be used in “Detectsound” to update the normative data for the ERB width and K factor, and the broadening factor of auditory filters with hearing loss. These data are necessary in “Detectsound” to make predictions when only absolute hearing thresholds are known (Section 3.2.3 and Table 3.1).

The results from the hearing experiment are also useful to test the validity of the “Detectsound” with masked threshold predictions. Essentially, “Detectsound” does the reverse process than SHAPE: masked thresholds are predicted based on known auditory filter parameters (ERB, K). To date, only the results of the first 6 normal-hearing subjects are available. Section 4.2 describes the predictions of “Detectsound” for the subjects taken individually, and Section 4.3 deals with group average data. Section 4.4 compares the original and new versions of “Detectsound”.

Data are also currently being collected in our laboratory using maskers other than white noise: pink noise, filtered pink noise and two industrial noises. These results are too preliminary for a detailed analysis in this chapter. Section 4.5 discusses some early findings.

4.2 For normal hearing individuals

Figure 4.1 to 4.3 show the absolute hearing thresholds, ERB widths and K factors measured or derived from the validation study for one Subject Y.

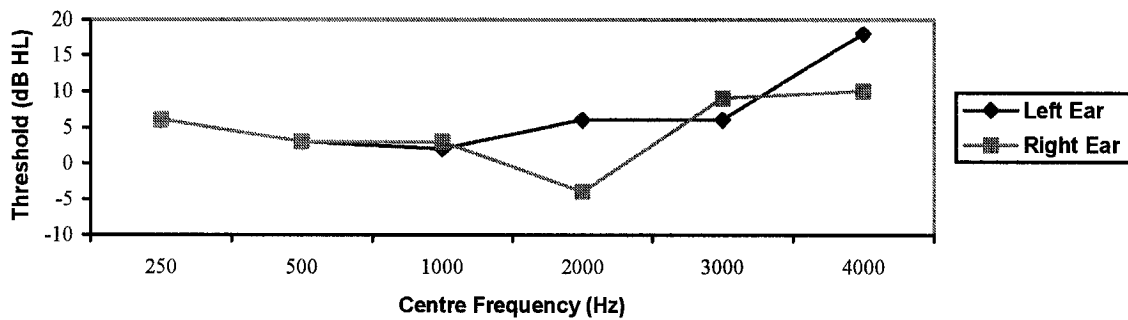


Figure 4.1: Measured absolute hearing thresholds of a Subject Y in our validation study

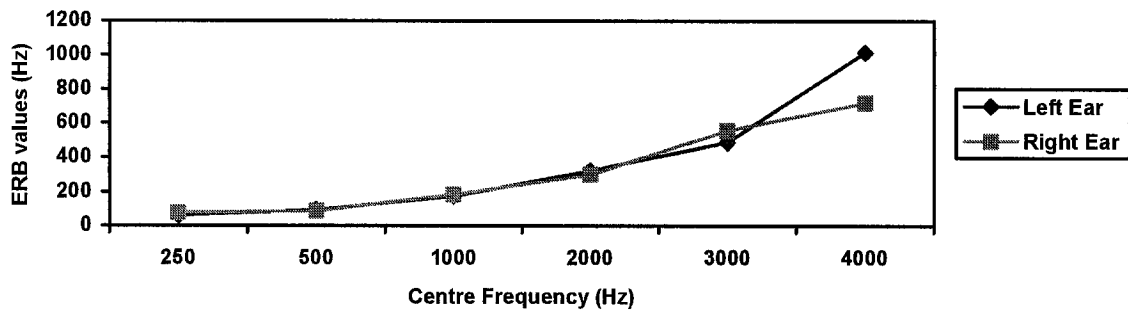


Figure 4.2: Derived frequency selectivity characteristics (ERB) of the same Subject Y

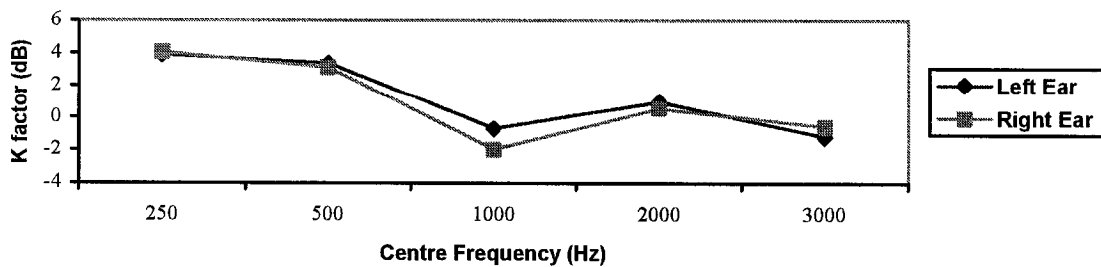


Figure 4.3: Derived K factors for Subject Y.

The masked threshold predictions of the new “Detectsound” for this subject are shown below in Figure 4.4. The measured results are for Subject Y and a masker white noise level at 80dB SPL. For the predictions, the K factors used were individual values derived for this subject in the hearing study.

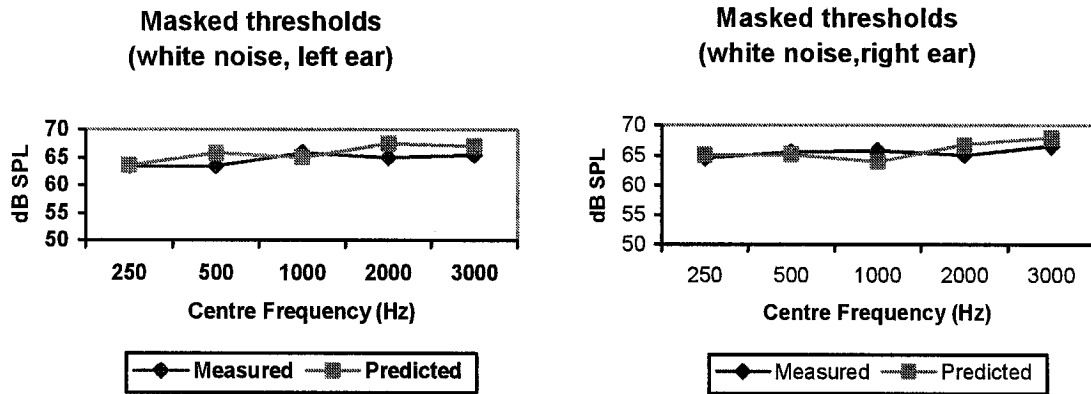


Figure 4.4: Predictions of new “Detectsound” (white noise at 80 dB SPL, individual K factors are used for correction) for Subject Y. The predicted masked thresholds are obtained by subtracting 12dB from lower boundary of design window.

As we can see, new “Detectsound” makes very good predictions in this case. The predicted masked thresholds at centre frequencies of 250, 500, 1k, 2k, and 3k Hz fit very well with the measured masked thresholds for this subject. The estimation errors, as reflected by the difference between predicted masked thresholds and measured masked thresholds, are usually small. This result is also confirmed by data collected with other subjects. Table 4.1 lists the estimation errors of new “Detectsound” for six normal hearing subjects. These subjects are tested in the same study as Subject Y (Subject 4 in Table 4.1). Estimation errors are computed individually.

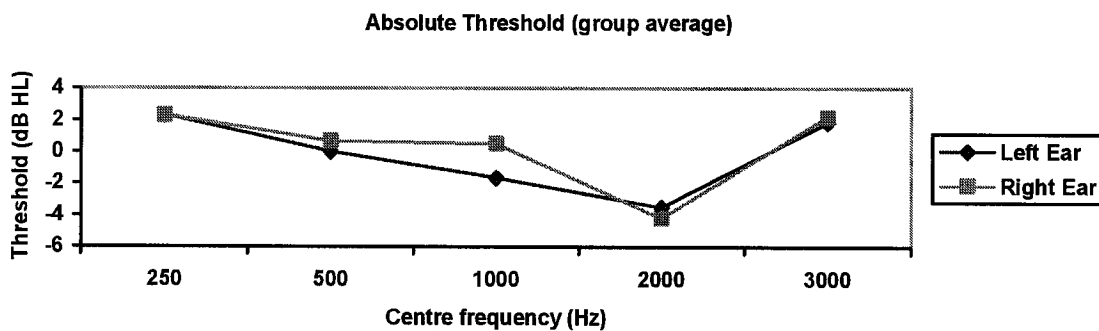
Table 4.1: Estimation errors for six normal hearing subjects (dB)

Centre Frequency		250Hz	500Hz	1000Hz	2000Hz	3000Hz
Subject 1	Left ear	+0.44	-0.74	-1.49	+0.12	+0.02
	Right Ear	+0.86	+1.41	-0.99	+0.11	-0.15
Subject 2	Left ear	+3.46	-0.46	-1.49	+0.36	+1.02
	Right Ear	+0.04	-0.35	-0.63	+0.80	+0.20
Subject 3	Left ear	+0.01	+0.79	+1.19	+4.00	+1.20
	Right Ear	+0.46	+1.55	-0.36	+0.20	+1.91
Subject 4	Left ear	+0.08	+2.26	-0.81	+2.45	+1.48
	Right Ear	+0.55	-0.41	-1.90	+1.71	+1.41
Subject 5	Left ear	+0.42	-0.59	-2.36	+0.17	-0.08
	Right Ear	+0.22	-1.09	-1.79	-0.31	+0.15
Subject 6	Left ear	+0.63	-0.76	-1.07	-0.97	+0.72
	Right Ear	+0.26	-1.50	-1.00	-0.33	+0.14
Group average		+0.62	+0.01	-1.06	+0.69	+0.67

The group average estimation error lies between 0.01dB to 1.06dB across all measured frequencies.

4.3 For a group of normal hearing individuals

As we have seen above, new “Detectsound” shows good predictability at individual situations. Now we want to test its validity and estimation error over group situation using data from some specific population (here for 6 subjects). The hearing status (group average) and K factors (group average) are shown in Figures 4.5 and 4.6.



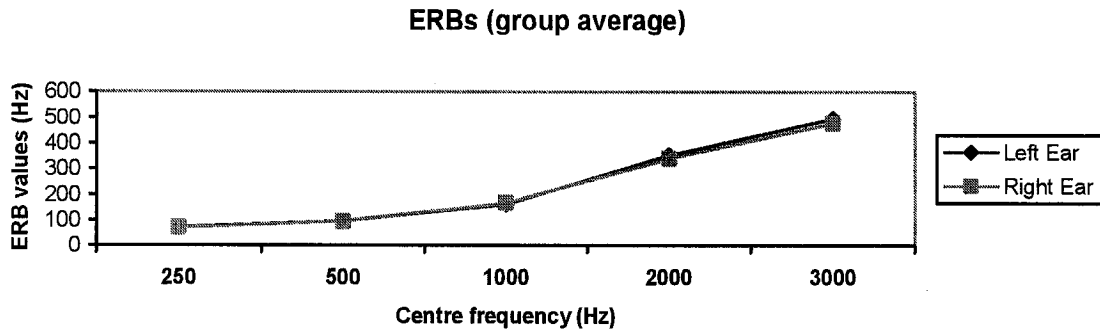


Figure 4.5: Hearing characteristics (absolute hearing thresholds and ERB) of the target population (6 subjects).

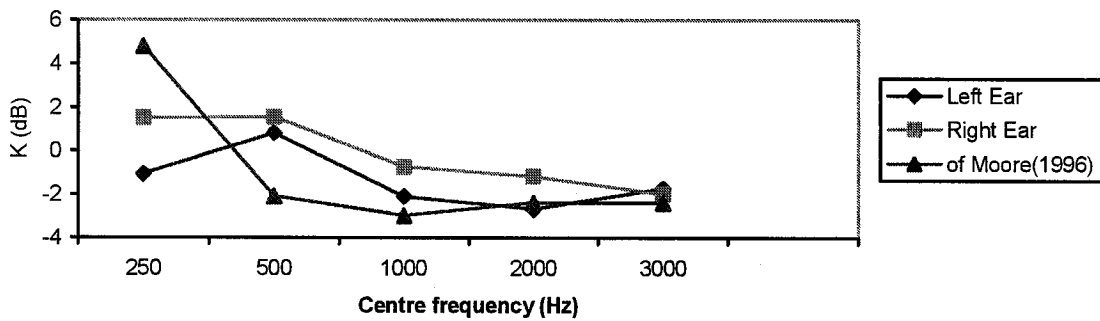
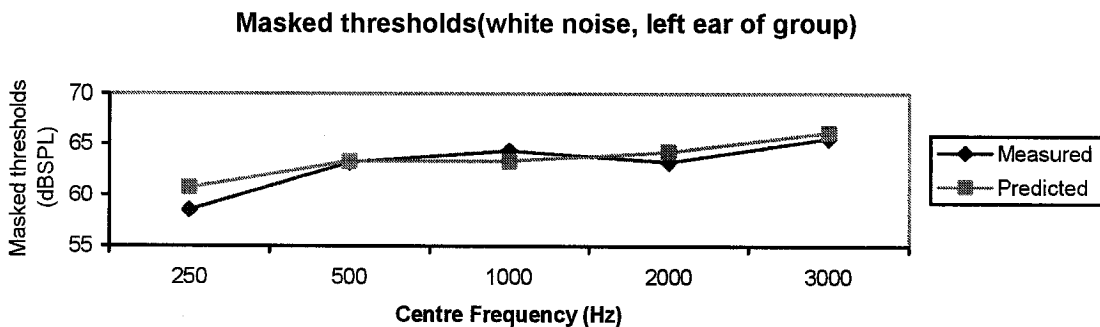


Figure 4.6: "Detection efficiency" factor K for this population group (6 subjects). The values from Moore's study (1996) are shown for comparison.

The predicted masked thresholds (as obtained by subtracting 12dB from lower boundary of the design window) and the measured masked thresholds (average of measured masked thresholds for each members of this group) are described in Figure 4.7. White noise masker level for measuring and predicting masked thresholds is 80dB SPL.



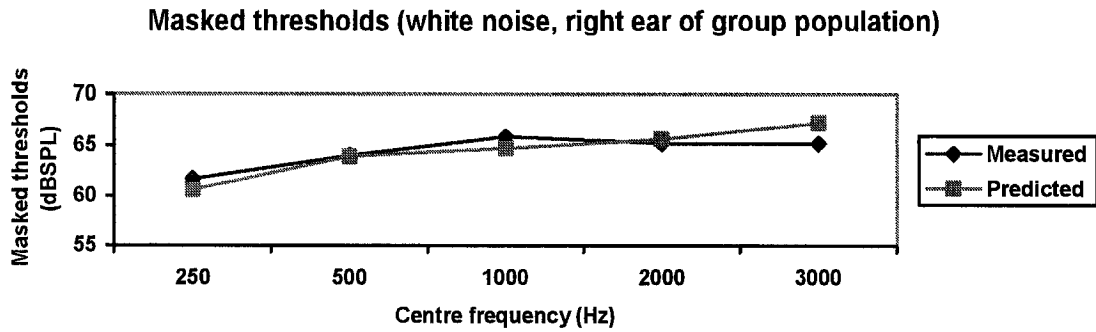


Figure 4.7: Predictions by the new “Detectsound” for a specific normal hearing population (6 subjects). Measured masked thresholds are obtained from one of our laboratory studies; predicted masked thresholds are obtained by subtracting 12dB from lower boundary of design window; average measured K values are used for correction.

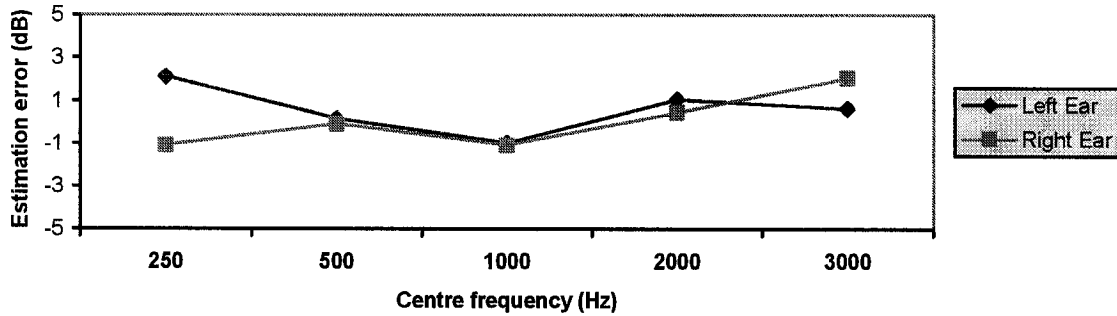


Figure 4.8: Estimation error by the new “Detectsound”

Across the frequencies from 250Hz to 3000Hz, the predictions and measurements fit very well. The estimation error distribution in this case is described by Figure 4.8. Across all frequencies and all ears, the average error is 0.3dB only (under-estimation).

4.4. A comparison between the original “Detectsound” and the new “Detectsound”

It will be very interesting to compare the predictability of the new “Detectsound” and original “Detectsound” against a same set of measured data. Such a comparison can prove whether our improvements have enhanced the precision of predictions. Here we give an example of the comparison.

The population consists of the 6 normal hearing subjects from our laboratory study. Related hearing status has been displayed by Figures 4.5 and 4.6. The background noise is white noise at 80 dB SPL. No hearing protector is worn. The predictions of the new and original “Detectsound” are shown in Figure 4.9. As we can see, the original “Detectsound” tends to predict higher masked thresholds across most frequencies compared with new “Detectsound”. The average overestimation is 3.05 dB across frequencies from 125 to 3150Hz.

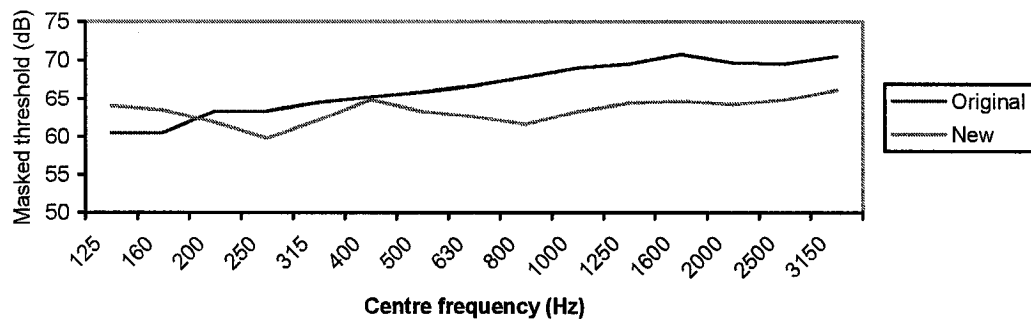


Figure 4.9: Predicted masked thresholds from the new and the original “Detectsound” over the entire frequency range of the design window

In a former validation study (Hétu & Tran Quoc, 1994), researchers found that the original “Detectsound” generally led to slight overestimation of the masked thresholds. The predicted masked thresholds were about 2 dB higher than the observed values. Inferred from this finding, it can be concluded that the prediction of the new “Detectsound” may give slight underestimation of masked thresholds by 1dB.

The comparison test using our own observed masked threshold data confirms the overestimation tendency of the original “Detectsound”. It also indicates that the prediction of new “Detectsound” is actually much closer to real observed masked thresholds. Figure 4.10 shows the predictions made by the original “Detectsound” and new “Detectsound” against the observed masked thresholds measured in an ongoing laboratory study. As we can see, the average overestimation of the original “Detectsound” is 4dB at frequencies of 250, 500, 1k, 2k and 3kHz. New “Detectsound” carries an average underestimation of 0.3dB.

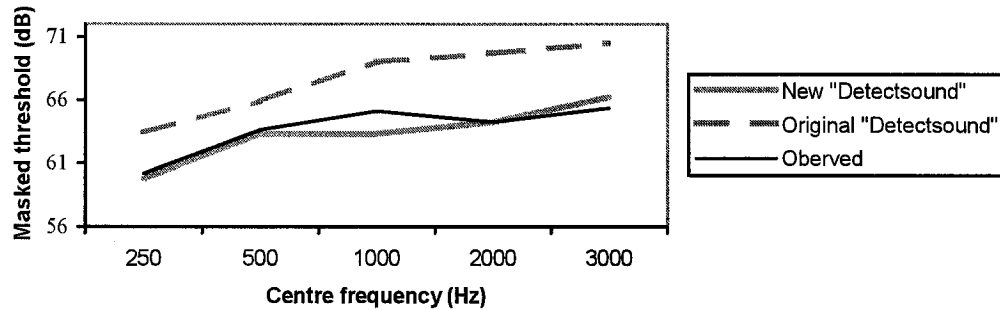


Figure 4.10: Predictions of original and new “Detectsound”, and observed masked thresholds at 5 pure-tone frequencies for white noise masker (80 dB SPL)

4.5. Discussion: Further improvement in describing background noise

Thus far, the new “Detectsound” model has shown fairly good predictability for individuals or for groups of normal hearing subjects, and this indicates the general validity of applying this model and approach for warning signal perception. With the incorporation of more complete normative data for frequency selectivity and estimation procedures for describing frequency selectivity as a function of hearing loss, new “Detectsound” can make even more accurate predictions about the hearing perception characteristics for specific populations.

Some more work may be necessary in the future to reflect the difference in detection efficiency with different noises. In our ongoing laboratory study, preliminary results appear to indicate some differences exist among the masked thresholds by different masker noises of the same level. For example, at 1250Hz, the difference in masked thresholds for pink noise and cable swagger noise for a normal-hearing subject reaches 4.5dB. From Equation(13), the functions $W(f)$ and $N(f)$ (about 45dB/Hz for both noises) are identical in this case. The only factor that can account for the difference in masked thresholds is K . This implies that the detection efficiency factor K may vary with noise types (even for the same person). This phenomenon may be explained by the temporal pattern of the noises. Swagger noise is an impact noise and its level fluctuates in time. Subjects may be able to detect the signal during the quieter segments of the noise. In contrast, pink noise is more stable.

In the future, the predictions of “Detectsound” model could be made to vary with background noise types. A possible implementation comes from the adjustment of K values. At present, K is assumed to be related to frequency and depends on each individual. Perhaps K should also be dependent on noise type. Related data will be available from the validation study with multiple noises carried out in our laboratory.

Chapter 5. Applications of new “Detectsound”

The original version of “Detectsound” could only apply to target populations or individuals whose absolute thresholds were known. With the incorporation of the auditory filter characteristics for individual workers, and the incorporation of standardized data on threshold estimation, the new “Detectsound” can be applied to a wider range of situations. This chapter illustrates several applications.

5.1 Application to an individual whose hearing status is fully known

Figure 5.1 shows an example for a specific individual whose hearing status (absolute thresholds, ERBs and K factors) is fully known from measurements. In this case, the design window for a warning signal perception produced by “Detectsound” applies specifically for this person.

The screenshot shows the 'DetectSound - Individual File' window. The 'Project' is 'Example_project - Public'. The individual's 'Identification Number' is '10', 'First Name' is 'Subject1', and 'Date of Creation/Modification' is '01/04/03 12:16:36'. The 'Response' is 'Public'. The 'Hearing Thresholds' section shows 'Statistical Thresholds' and 'Measured Thresholds' for both 'Left Ear' and 'Right Ear'. The 'ERB' section shows 'Statistical ERB' and 'Measured ERB' for both 'Left Ear' and 'Right Ear'. The 'Measured ERB' values are: 250 Hz (79.74), 1 KHz (168.94), 3 KHz (447.86), 500 Hz (110.67), 2 KHz (307.11), and 4 KHz (631.15). The window has 'OK' and 'Cancel' buttons at the bottom.

Hearing Thresholds					
Left Ear			Right Ear		
Frequency	Statistical	Measured	Frequency	Statistical	Measured
125 Hz	-4	-2	125 Hz	-2	-2
250 Hz	-4	-2	250 Hz	-2	-2
500 Hz	-2	-2	500 Hz	-2	-2
1 kHz	-2	-8	1 kHz	-8	-4
2 kHz	-8	-8	2 kHz	-4	-4
3 kHz	-9	-8	3 kHz	-6	-
4 kHz	-8	-8	4 kHz	-	-
6 kHz	-8	-	6 kHz	-	-
8 kHz	-8	-	8 kHz	-	-

ERB					
Left Ear			Right Ear		
Frequency	Statistical	Measured	Frequency	Statistical	Measured
250 Hz	68.62	149.85	250 Hz	79.74	168.94
1 KHz	-	398.35	1 KHz	-	447.86
3 KHz	-	604.32	3 KHz	-	631.15
500 Hz	71.63	344.3	500 Hz	110.67	307.11
2 KHz	-	-	2 KHz	-	-
4 KHz	-	-	4 KHz	-	-

Figure 5.1: An individual whose hearing status is fully known from measurements.

Figure 5.2 shows the produced design window for an example background noise of 87.2dB(A) recorded in a machinery room on a large ship. As we can see, the width of the design window is 13dB across most frequencies. But for the frequencies below 200Hz, the width of the design window narrows with the decrease of frequency. The reason is that the lower boundary approaches the 105dB SPL limit across frequencies lower than 200Hz. In this application, you want to put a certain worker to a specific workstation and know his/her hearing status exactly. Thus, with “Detectsound”, you can know the exact optimal characteristics for warning sounds.

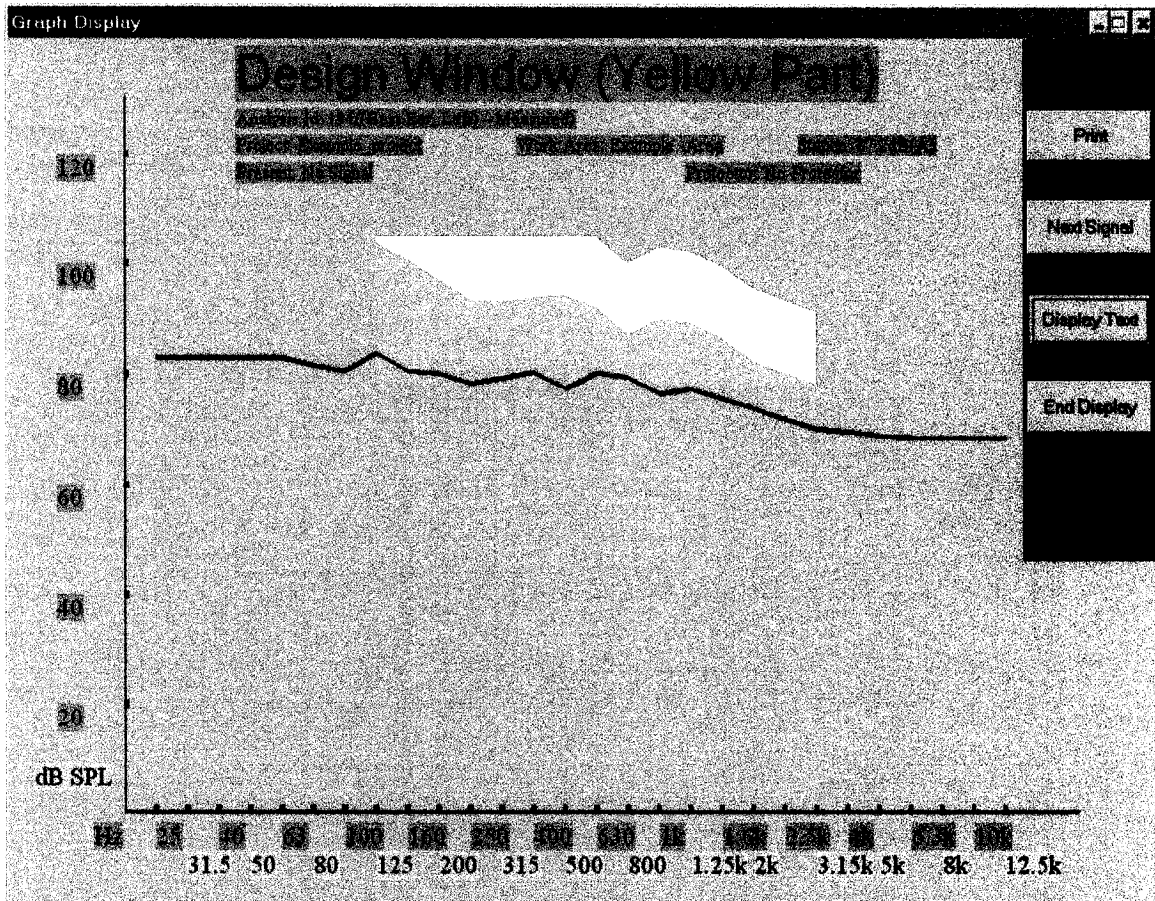


Figure 5.2: Warning signal design window for the specific individual of Figure 5.1 (shaded area). The background noise level is 87.2 dB(A) (solid line). Individual K factors were adopted.

5.2. Application to an individual whose absolute thresholds are known

Figure 5.3 shows an example for a specific individual whose absolute thresholds are known only. In this case, new “Detectsound” provides ways of estimating ERBs based on the statistical relationship between hearing threshold and ERB width at different frequencies (see Section 3.2.3.a).

Project: [1] Example_project - Public

Individual:
 Identification Number: 7
 First Name: HL6
 Date of Creation/Modification: 01/06/03 13:21:16
 Family Name:
 Responsible: Public

Hearing Thresholds

Statistical Thresholds						Measured Thresholds						Clear Threshold Windows					
Left Ear			Right Ear			Left Ear			Right Ear			Left Ear			Right Ear		
125 Hz	15	<input checked="" type="checkbox"/>	1 kHz	18	<input type="checkbox"/>	125 Hz	16	<input type="checkbox"/>	1 kHz	18	<input type="checkbox"/>	125 Hz	16	<input type="checkbox"/>	1 kHz	18	<input type="checkbox"/>
250 Hz	15	<input checked="" type="checkbox"/>	2 kHz	45	<input type="checkbox"/>	250 Hz	16	<input type="checkbox"/>	2 kHz	51	<input type="checkbox"/>	250 Hz	16	<input type="checkbox"/>	2 kHz	51	<input type="checkbox"/>
500 Hz	15	<input type="checkbox"/>	3 kHz	57	<input type="checkbox"/>	500 Hz	16	<input type="checkbox"/>	3 kHz	59	<input type="checkbox"/>	500 Hz	16	<input type="checkbox"/>	3 kHz	59	<input type="checkbox"/>
			4 kHz	64	<input type="checkbox"/>				4 kHz	60	<input type="checkbox"/>				4 kHz	60	<input type="checkbox"/>
			6 kHz	53	<input type="checkbox"/>				6 kHz	68	<input type="checkbox"/>				6 kHz	68	<input type="checkbox"/>
			8 kHz	53	<input checked="" type="checkbox"/>				8 kHz	68	<input checked="" type="checkbox"/>				8 kHz	68	<input checked="" type="checkbox"/>

ERB

Statistical ERB						Measured ERB						Clear ERB Windows					
Left Ear			Right Ear			Left Ear			Right Ear			Left Ear			Right Ear		
250 Hz	70	<input checked="" type="checkbox"/>	1 KHz	164	<input checked="" type="checkbox"/>	250 Hz	70	<input checked="" type="checkbox"/>	1 KHz	164	<input checked="" type="checkbox"/>	250 Hz	70	<input checked="" type="checkbox"/>	1 KHz	164	<input checked="" type="checkbox"/>
500 Hz	94	<input checked="" type="checkbox"/>	2 KHz	343.06	<input checked="" type="checkbox"/>	500 Hz	94	<input checked="" type="checkbox"/>	2 KHz	343.06	<input checked="" type="checkbox"/>	500 Hz	94	<input checked="" type="checkbox"/>	2 KHz	343.06	<input checked="" type="checkbox"/>
			3 KHz	1312.96	<input checked="" type="checkbox"/>				3 KHz	1312.96	<input checked="" type="checkbox"/>				3 KHz	1312.96	<input checked="" type="checkbox"/>
			4 KHz	2650.42	<input checked="" type="checkbox"/>				4 KHz	2650.42	<input checked="" type="checkbox"/>				4 KHz	2650.42	<input checked="" type="checkbox"/>

Buttons: OK, Cancel

Status: Ready NUM

Figure 5.3: An individual whose absolute threshold are known and ERBs statistically estimated.

The produced design window (Figure 5.4) can be regarded as being applicable to the median individual (in terms of frequency selectivity) among all individuals with absolute thresholds identical to the target individual. In this situation, you know the hearing threshold of a certain individual, but are uncertain with his frequency selectivity (which is hard to measure by conventional ways). With the estimation of frequency selectivity, it is possible to get a design window for people with similar thresholds. The produced design window provides the most likely estimation of the perception characteristics for warning sounds. Comparing Figure 5.4 with Figure 5.2, we can find

obvious elevation of design window at higher frequencies. This reflects the effect of different hearing thresholds or ERB (as the background noise levels stay unchanged).

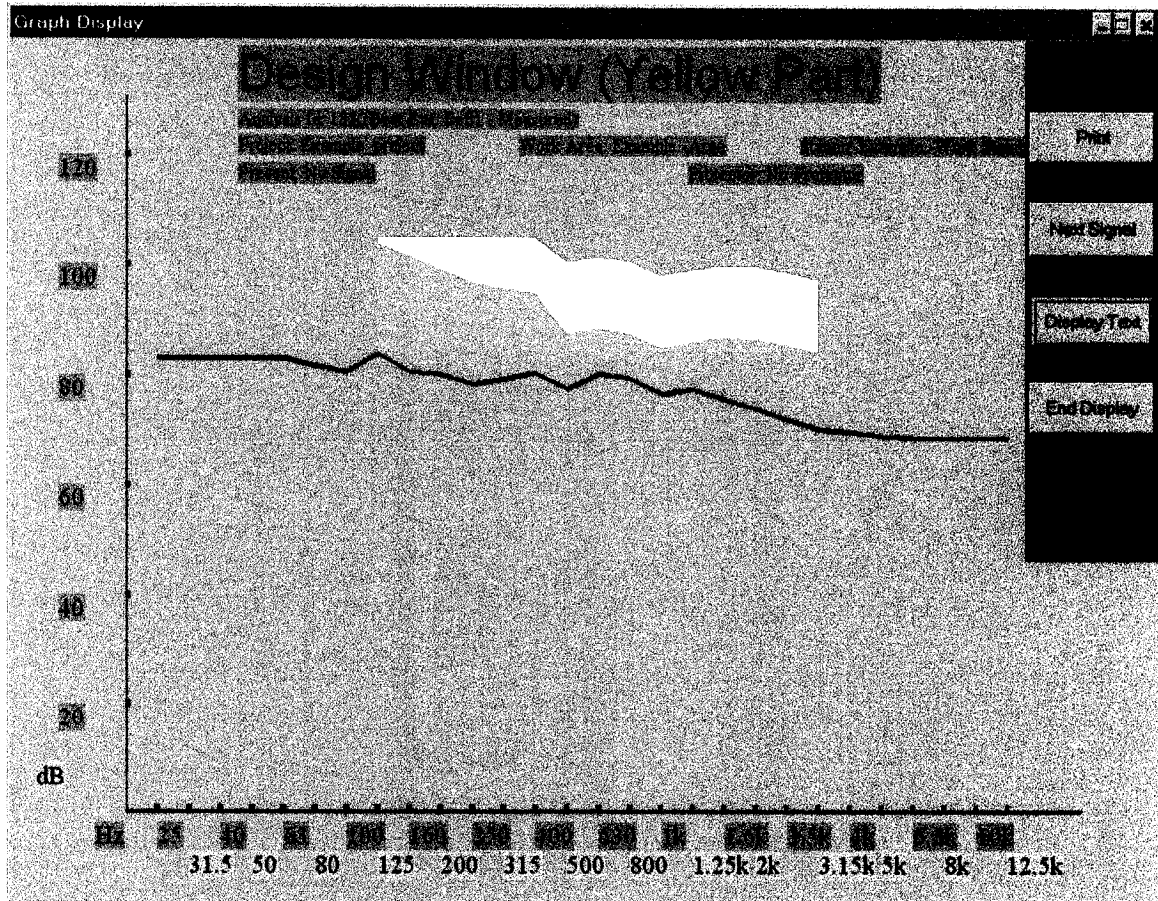


Figure 5.4: Warning signal design window for the individual of Figure 5.3 (shaded area). The background noise level is 87.2dB(A)(solid line). Default K factors were adopted.

5.3. Application to a target population

There are many situations where the hearing thresholds and frequency selectivity of individual workers of the target population are unknown; this is quite common in industrial worksites. Also, there are many situations in practice, when planning new plants or making projections for the future where the individual hearing status cannot be known. The new “Detectsound” provides ways of estimating hearing status for a target population of given age, sex and employment history, and produces a design window based on these assumptions.

When entering data for a new individual, if the user chooses “Statistical Thresholds”, a window as shown in Figure 5.5 will pop up automatically.

The screenshot shows a software window titled "Estimates Threshold ----- ISO1999(1989)". The window contains two main sections: "PERSONAL FACTORS" and "EMPLOYMENT HISTORY".

PERSONAL FACTORS:

- Name: Population
- Age: 50
- Sex: Male
- Percentile: 10%
- Effect Of: Interaction

EMPLOYMENT HISTORY:

- Employment Type: Industry Worker
- Noise Level dB(A): 97
- Years of Noise Exposure: 25
- Impact Noise: No

At the bottom of the window, there are two buttons: "Do Estimation" and "Cancel".

Figure 5.5: The interface to define the characteristics of a target population

The user can define sex, age, length of exposure to noise, noise level, and noise type (impact noise or not) for the target population. It is also possible to opt for the estimation based on a certain percentile level (50% or 10%) and the hearing loss factor to be considered (age effect, noise exposure, or the interaction of both). Absolute thresholds and ERBs are then estimated automatically based on the above choices. Figure 5.6 illustrates the estimated outcome for a specific case.

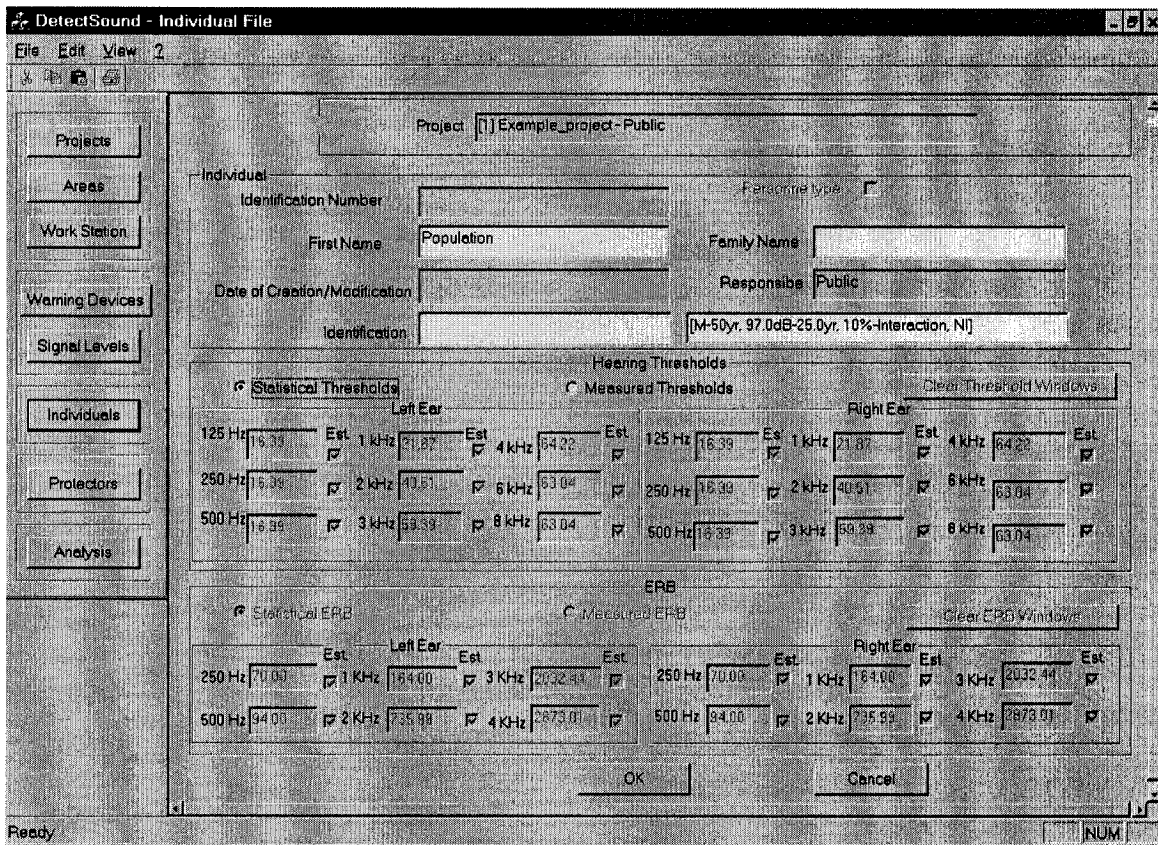


Figure 5.6: Estimated hearing status of a specific population (50 years old, male, exposed to noise at 97dB(A) for 25 years, percentile of 10%, effects of age, noise exposure and their interactions).

If the population is to be placed in a noisy worksite (background noise level at 87.2 dB(A)), the perception characteristics for warning signals are shown in Figure 5.7.

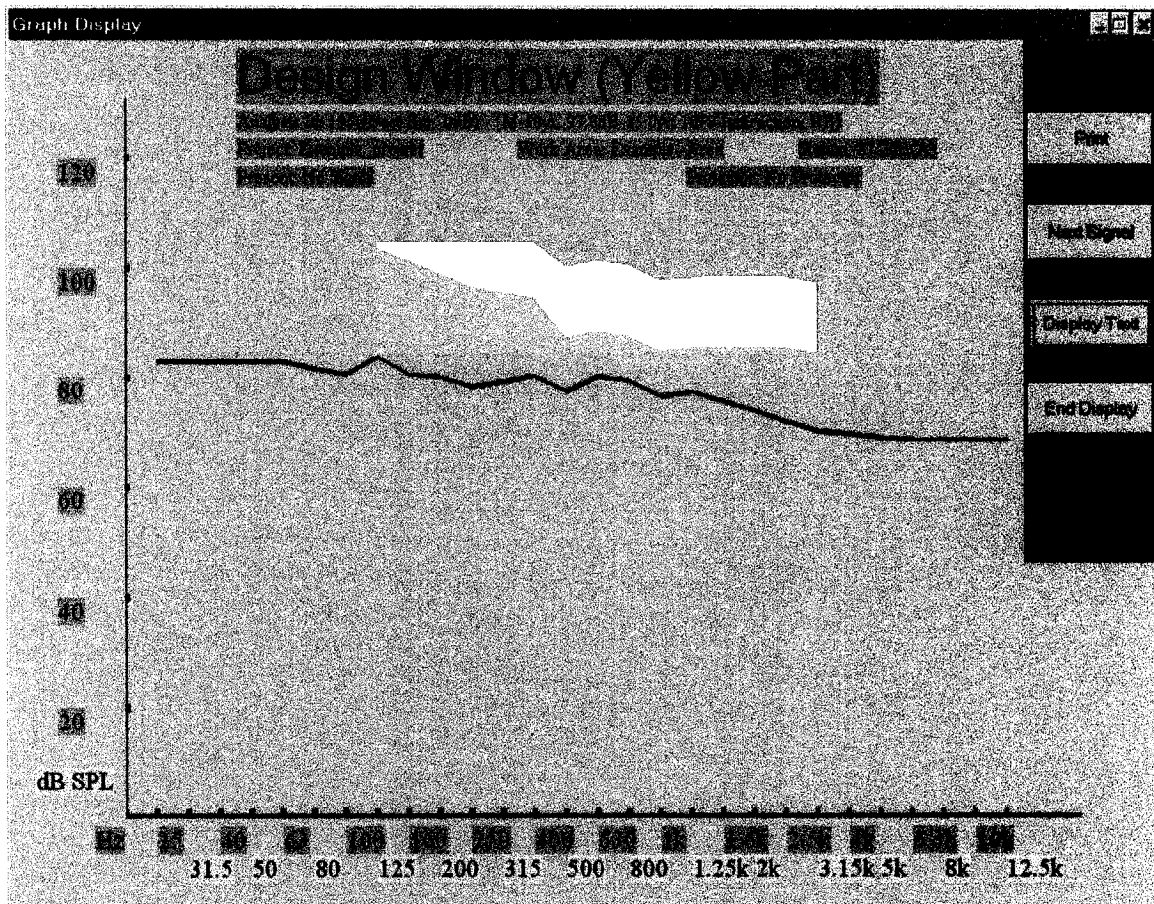


Figure 5.7: Design window for warning signals of a target population as defined in Figure 5.5 and 5.6 (shaded area). The background noise level is 87.2dB(A) (solid line). Default K factors were adopted.

5.4 Application to heterogeneous populations

With the new “Detectsound”, it is possible to predict the “overall” warning signal design window across a population of workers sharing the same work environment. This is very useful when there is a need to adjust a warning signal in a work area accessible to many workers, each with a potentially different hearing status. For example, let’s assume that there is a group of 7 workers working closeby in a work area. They are all male, have been exposed to noise of 97dB(A) (which equals to the noise level of using Hitachi cutter (marble) by construction workers) since the age of 25 yr., and their exposure lengths are 0,5,10,15,20,25, 30 years respectively. The estimated absolute hearing thresholds (as predicted by ISO 1999) are shown in Figure 5.8. The decreasing of their frequency

selectivity with hearing sensitivity loss (as predicted by “Detectsound” model) is shown in Figure 5.9.

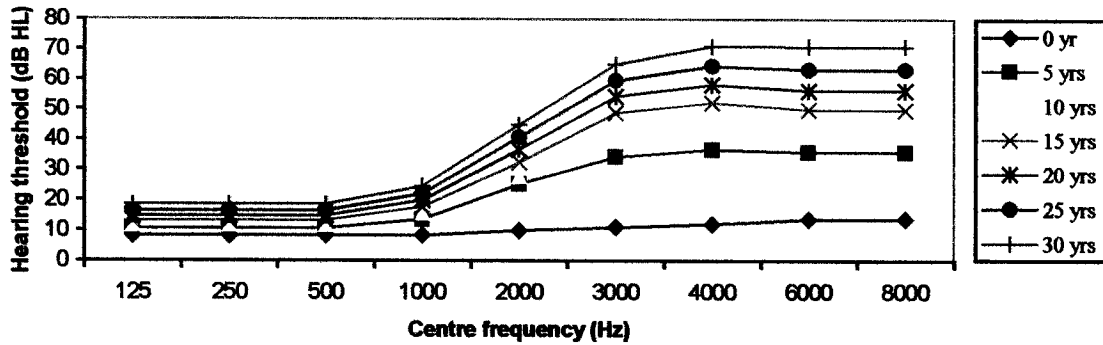


Figure 5.8: Predicted absolute threshold shifts associated with age and noise exposure for a group of 7 workers. The estimations are made based on ISO 1999 (1989).

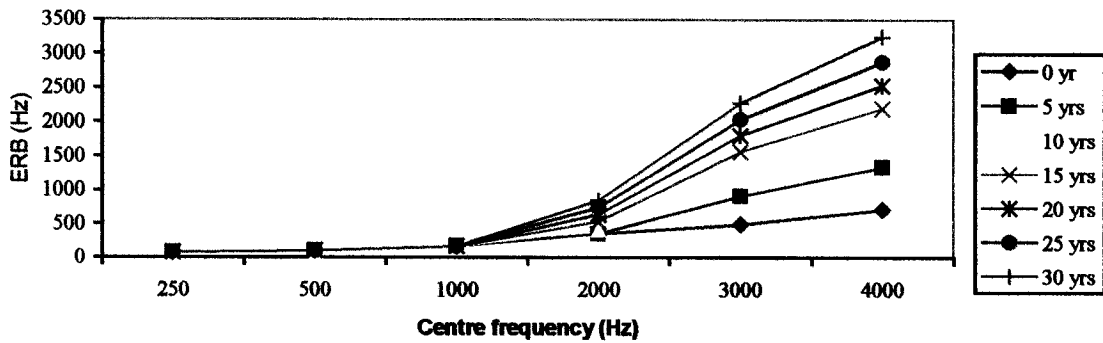


Figure 5.9: Predicted auditory filter broadening associated with age and noise exposure for a group of 7 workers. The estimations are made based on the normative data integrated in new “Detectsound”.

Figure 5.10 shows the upper boundary of conception window for each member of the group (under the background noise of 87.2dB(A)). The predicted lower boundaries are shown in Figure 5.11. As can be seen, the upper and lower boundaries become gradually elevated above 1000Hz due to the increased hearing loss. This means that each worker has his own optimal design window.

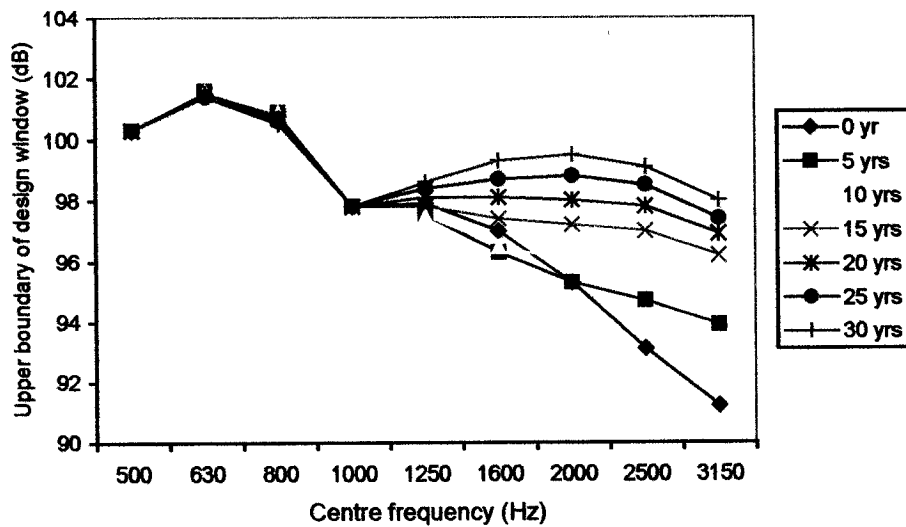


Figure 5.10: Predicted effect of hearing loss as reflected by the shifting of the upper boundary (13dB above lower boundary) of the warning signal design window under a certain workplace noise 87.2dB(A).

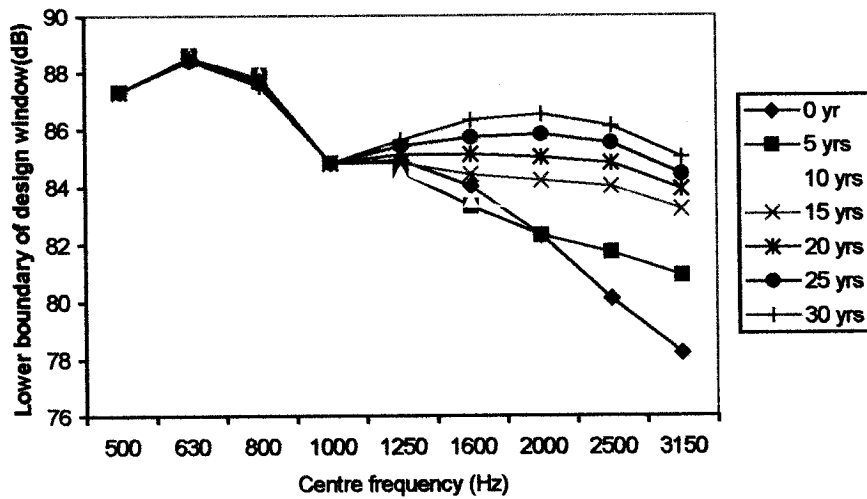


Figure 5.11: Predicted effect of hearing loss as reflected by the shifting of lower boundary of the design window by new “Detectsound” under a certain workplace noise (87.2dB(A)).

Now let’s consider the design window that would be suitable for all the members of the group. This overall design window, as formed by the “highest” lower boundary and

the “lowest” upper boundary, represents the range of optimal warning signal levels applicable for all these workers. Figure 5.12 shows the overall window. Warning signal levels within the range of the overall design window provide the best solution for the given population of workers.

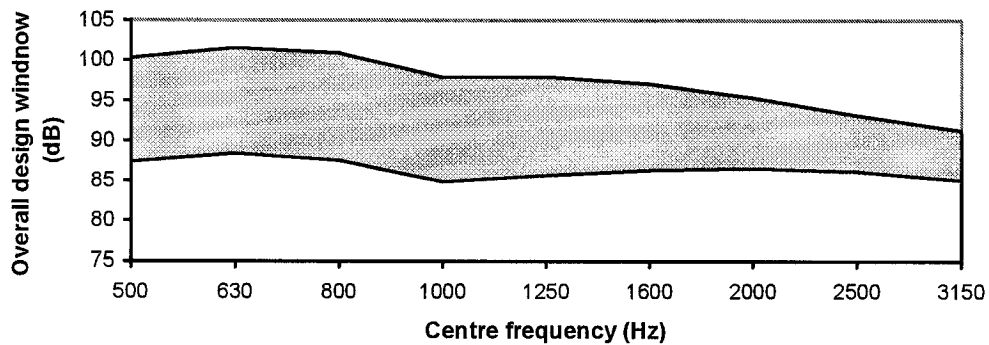


Figure 5.12: The overall design window for 7 workers in the group, which have been exposed to noise of 97dB(A) for 0,5,10,15,20,25 and 30 years respectively.

If the workers are wearing hearing protectors (here we use EAR-1000 earmuff as an example, see Figure 3.4 for details), the overall design window can be computed again. As shown in Figure 5.13, it has changed significantly. The lower boundary surpasses the upper boundary for frequencies higher than 2000Hz. This means, optimal warning signal levels can only be found at frequencies below 2000Hz (within part A in Figure 5.13). There are no optimal warning signal levels for frequencies higher than 2000Hz that would be suitable to all 7 workers. A warning signal may have been too loud for some workers (as falls into part B in Figure 5.13), but is still too low for other workers. The reason for such a cross over in Figure 5.13 is the too large attenuation of the protector for some workers; the noise falls below quiet thresholds. Above 2000Hz the upper and lower boundaries are determined by the absolute thresholds for the most exposed workers and by the masked thresholds for the least exposed workers. Similar narrowing can also be found for frequencies below 200Hz.

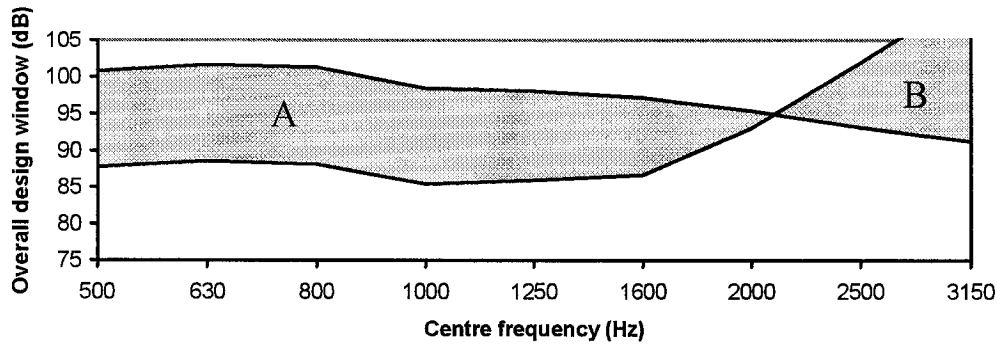


Figure 5.13: The overall design window for a group of 7 workers wearing a hearing protector and previously exposed to noise of 97dB(A) for 0,5,10,15,20,25 and 30 years respectively. Part A indicates the range of optimal warning signal levels applicable for all members. In part B, no optimal levels exist for frequencies beyond 2000Hz.

5.5. Discussion: Estimation of background noise by “OUÏE-2000”

As we have seen, new “Detectsound” can be easily applied to a specific individual, or a target population, or a group of different workers. The adjusted warning signal levels accordingly are effective for a specific individual, a target population, or a group of different workers as shown in the examples of Section 5.4. “Detectsound” is particularly useful to assess the interaction of hearing loss from different workers with the wear of hearing protectors. Even more complex situations can be envisaged, where some workers use hearing protectors and some do not. The adjustment of warning signals becomes a very difficult problem without a tool like “Detectsound”.

However, we have to notice that all these analysis are based on a specific workstation or confined work area with uniform background noise. This means, all the analysis results are only valid for a specific location, and we cannot necessarily generalize the results to the whole workplace as the noise distributions at different workstations are generally different. This limitation can be improved with the integration of “OUÏE-2000”. As we have introduced in Section 1.3, “OUÏE-2000” can be used to estimate the noise levels of any workstation within a workplace. With such integration, “Detectsound” will be able to make predictions about the optimal warning signal levels valid for each workstation and individual within a specific workplace.

Chapter 6. Conclusions

In this thesis, a computerized tool called “Detectsound” for predicting the capability of workers to detect auditory warning signals in noise was comprehensively improved. Like in the original version, the new “Detectsound” model allows to adjust the levels of auditory warning signals and to provide the best solution for safety based on the hearing status of workers, level of the background noise and attenuation of hearing protectors. The main enhanced features for new “Detectsound” model are: (1) individual hearing status has been taken into account, (2) normative data on threshold estimation associated with noise exposure and age (ISO 1999, ISO 7029) has been incorporated into, (3) more recent and accurate data reflecting frequency selectivity decrease with hearing sensitivity loss has been integrated, and (4) the user interface of the implementation program has been greatly improved.

“Detectsound” can now be more easily applied to analyze the perception of warning signals based on measured or estimated hearing status data (absolute thresholds, frequency selectivity, detection efficiency factor). The predictions of new “Detectsound” have been validated against measured data obtained in an ongoing laboratory study using white noise maskers. A comparison between the original and new “Detectsound” shows that the predictions of the new “Detectsound” are closer to measured data. As validated against the measured data obtained in an ongoing laboratory study, new “Detectsound” carries a slight underestimation of 0.3dB for white noise, whereas the original “Detectsound” tends to overestimate by 4dB in this case.

A range of options is now available to specify or estimate the absolute thresholds and frequency selectivity of the target individual(s), and the perception for auditory warning signals can be analyzed based on the specified or estimated hearing status. According to the analysis result of new “Detectsound”, the warning signal levels at workplaces can be optimized to suit the needs of a specific individual, a group of individuals with similar hearing thresholds, or heterogeneous populations. Therefore, new “Detectsound” can be applied to increase safety in the workplace in a range of situations. It is especially useful when the effects of hearing protectors need to be accounted for and when warning signals are to be optimized simultaneously for a range of individuals with

different hearing status. Simulations have also shown that under some conditions of noise and hearing status, no optimal warning signal levels can be found at some frequencies. This would occur, for example, when workers with normal and highly elevated hearing thresholds share a common work area where hearing protectors are worn. The design and adjustment of warning devices to assure work safety in such cases can be very complex without a tool like “Detectsound”. Thus, “Detectsound” provides a practical advancement for the safety of workers in noisy industrial settings.

In the future, the “Detectsound” model can be further improved by taking into account the difference in masked thresholds for different noises of identical spectrum level but different temporal structures, such as impact noises. This could be done by including a noise factor into the detection efficiency. The normative data for estimating frequency selectivity may also need to be updated. Air conduction thresholds and bone conduction thresholds may be included separately to reflect the hearing loss due to the middle ear and to inner ear damage, as the latter is related to frequency selectivity decrease. The relationship between the hearing sensitivity loss and frequency selectivity decrease needs to be described more accurately. If the model for estimating noise distributions within industrial sites (OUIE-2000) can be integrated with new “Detectsound”, the analysis result of new “Detectsound” will be applicable automatically for any area within a specific workplace. Such results may not only be used to set the optimal the level of warning signals, but also be used to find the best solution in terms of number of warning devices and wall locations to install. This would provide a very useful tool for designing optimal installation of auditory warning signals in a work area with non-uniform noise levels and co-workers with different hearing status.

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