Noise induced hearing loss: Screening with pure-tone audiometry and speech-in-noise testing
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General introduction
Hearing impairment is a highly prevalent sensory deficit in the human population. The World Health Organization estimated that globally 278 million people have a permanent hearing loss of more than 40 dB HL (WHO, 2012), and when including milder losses (> 25 dB HL), this number increases to an estimated 642 million, which is almost 10% of the world population (WHO, 2006).

Since good hearing is essential for daily communication and social interaction, hearing damage can be seriously disabling. Worldwide, hearing loss is the second leading cause of disability (Mathers et al, 2003). Hearing impairment negatively affects physical, cognitive, and psychosocial function, by generating burdening effects such as distress, loneliness, depression, and social isolation (Mulrow et al, 1990; Carabellese et al, 1993; Cacciatoré et al, 1999; Kramer et al, 2002; Arlinger, 2003; Nachtegaal et al, 2009). As a result, hearing impairment can have important implications for the quality of life (Arlinger, 2003; Chia et al, 2007)

Hearing loss is commonly classified as conductive, sensorineural, or mixed. Conductive hearing loss is caused by a mechanical defect interfering with sound transmission through the external and middle ear to the cochlea, affecting the mobility of the drum and/or the ossicles, thereby reducing hearing sensitivity (Sataloff & Sataloff, 1993). See Figure 1.1 for an overview of the anatomy of the ear. When hearing impairment is due to pathology in the cochlea or in the auditory nerve, the loss is referred to as a sensorineural hearing loss. In addition to reduced hearing ability for soft sounds, persons with sensorineural hearing loss can have suprathreshold deficits leading to the distortion of sounds (Plomp, 1986), causing difficulty in understanding speech, especially in adverse conditions such as in noise and reverberation. This type of hearing loss is largely irreversible and cannot be medically or surgically corrected.

Sensorineural hearing loss can be caused by a wide range of etiologies and its characteristics vary accordingly. The leading causes of acquired sensorineural hearing loss are age-related hearing loss, also referred to as presbyacusis, followed by noise-induced hearing loss (NIHL) (Rabinowitz, 2000; Mathers et al, 2003). Presbyacusis is a multifactorial hearing loss initially affecting the high frequencies and becoming progressively worse with advanced ageing (Albera et al, 2010).

**Epidemiology of NIHL**

Exposure to excessive noise causes a sensorineural hearing impairment referred to as noise-induced hearing loss. About 16% of the acquired hearing loss in adult workers worldwide is attributable to occupational noise exposure (Nelson, 2005). In the Netherlands, this is estimated to be 13 to 22% (Hoeymans et al, 2005). In addition, estimations demonstrate that 10 to 15% of the Dutch labor force is exposed to damaging noise levels during their work (Hoeymans et al, 2005). As a result, NIHL is the most frequently reported occupational disease in the Netherlands (Van der Molen
& Lenderink, 2012). Averaged over the past five years, 39% of occupational disease reports concerned NIHL, the majority of which came from the construction industry (Van der Molen & Lenderink, 2012).

Outside of work, loud sounds during recreational activities, such as visiting music concerts or dance events and listening to personal music players, may reach excessive noise levels as well. The addition of these effects is of growing concern, because an increasing percentage of noise-exposed employees also experiences exposure to noise during leisure time (Sorgdrager & Dreschler, 2010). Although evidence supporting the relationship between exposure to leisure noise and hearing loss remains ambiguous (Meyer-Bisch, 1996; Mostafapour et al, 1998; Niskar et al, 2001; Biassioni et al, 2005; Shah et al, 2009; Zhao et al, 2009), any exposure to noise of significant intensity and duration increases the risk of hearing damage. Average leisure noise levels are high enough to theoretically cause NIHL when exposed to for longer periods of time (SCENIHR, 2008). This is particularly important among those with higher susceptibility to noise (Biassoni et al, 2005) or among those who also work in a job with significant noise exposure.

Figure 1.1. Anatomy of the ear.
Moreover, hearing losses from many causes are additive (ISO-1999, 1990; Albera et al, 2010). As a result, NIHL has become a major cause of hearing loss in the ageing population, producing hearing impairment sooner than would occur from ageing alone.

**NIHL pathology and symptoms**

NIHL is usually a bilateral symmetrical sensorineural hearing disorder, arising from damaged structures in the inner ear due to prolonged and repeated exposure to loud noise. The mechanism of noise-induced hearing loss involves the destruction of hair cells in the organ of Corti within the cochlea. See Figure 1.2. for a schematic representation of the organ of Corti.

The organ of Corti contains approximately 15,000 hair cells arranged in rows; one row of inner hair cells (IHCs) and three to five parallel rows of outer hair cells (OHCs). Each hair cell has tiny hair-like structures called stereocilia. When these stereocilia are deflected, ion channels are opened, causing the release of neurotransmitters by depolarization of the hair cells. By this mechanism, the IHCs are responsible for converting the mechanical vibrations caused by the movement of the basilar membrane into electrochemical impulses in the auditory nerve (Sataloff & Sataloff, 1993; Plack, 2005). The outer hair cells, on the other hand, contribute to the cochlear amplifier; they amplify the movement of the basilar membrane by contracting when stimulated by sound (electromotility), increasing the input for the IHCs in case of low-level sounds (Brownell, 1990; Plack, 2005; Gorga et al, 2007). Thus, the outer hair cells are extremely important to hearing. However, they are also very fragile, and OHCs are the structures most susceptible for damage due to noise (Henderson et al, 2006) (see Figure 1.3).

![Schematic representation of the organ of Corti.](By Madhero88 2009 (Own work) [CC-BY-SA-3.0 (http://creativecommons.org/licenses/by-sa/3.0)], via Wikimedia Commons)
Noise can injure the ear in two different ways, depending on the type of exposure (Clark & Bohne, 1999; Dobie, 2001; Sataloff & Sataloff, 1993). Exposure to impulse noise such as explosive events, with peak levels exceeding 140 dB SPL, can directly cause mechanical damage (Clark & Bohne, 1999; Henderson et al, 2006). More common however, is the damage that develops over a longer period of chronic noise exposure that leads to several physical changes in the structures of the organ of Corti (Henderson et al, 2006; LePrell et al, 2007). Excessive noise increases the shearing movement between the basilar membrane and the tectorial membrane. As a direct result, mechanical changes in stereocilia arise (Sliwinska-Kowalska & Jedlinska, 1998); they are bended or floppy, or their tips are detached from the tectorial membrane (Gao et al, 1992; Nordmann et al, 2000). These stereociliary abnormalities are reversible over time, hence they are associated with a temporary threshold shift (TTS) (Gao et al, 1992; Henderson et al, 2006).

![Figure 1.3](image1.png)

Figure 1.3. Scanning electron micrographs of the normal (a) and damaged (b) cochlear sensory epithelium. In the normal cochlea, the stereocilia of a single row of inner hair cells (IHCs) and three rows of outer hair cells (OHCs) are present in an orderly array. In the damaged cochlea, hair cells are missing, and stereocilia are abnormal, leading to hearing loss.

If the ear is not given a chance to rest and recover, cells experience metabolic overload and go through a cascade of chemical events that leads to cell death (Talaska & Schacht, 2007). Intense metabolic activity of the hair cells generates an overproduction of reactive oxidative species (ROS) (Henderson et al, 2006; LePrell et al, 2007). Although these are natural byproducts of normal cellular life processes, they damage cells when present in excess (Bielefeld et al, 2005). Damage from ROS triggers hair cell death due to either necrosis or apoptosis (Hu et al, 2002). Although ROS formation is not limited to hair cells, the primary damage is concentrated on the OHCs (Sliwinska-Kowalska & Jedlinska, 1998; Talaska & Schacht, 2007).

The loss of outer hair cells leads to elevated hearing threshold levels, indicating a permanent threshold shift (PTS). However, only few OHC are required for normal hearing and according to several studies, up to 30-50% of OHCs can be absent before any measurable level of hearing loss is detected by audiometry, a phenomenon called OHC redundancy (LePage & Murray, 1993; Hamernik et al, 1996; Daniel, 2007). After continued exposure to noise, the audiogram displays a classic pattern of early NIHL, showing a notch in the area of 3-6 kHz, centred at 4 kHz (Sataloff & Sataloff, 1993; Dobie, 2001; Plack, 2005). The human ear is more susceptible to cochlear damage from sound in this specific frequency region, due to primary resonances of the external ear. Hearing damage progresses steadily over the initial decade of exposure, followed by a slowing increase in hearing loss (Rösler, 1994). With more severe noise exposures, the pathology spreads to include IHC death and degeneration of auditory nerve fibers and spiral ganglions (Talaska & Schacht, 2007).

Total OHC loss causes a reduction of 50-70 dB in hearing sensitivity (Kemp, 1986; Hamernik et al, 1989; Norton, 1992; Gao et al, 1992; Henderson et al, 2006). However, a beginning hearing loss in this frequency region usually does not significantly affect speech understanding in quiet, hence it is rarely perceived. With prolonged noise exposure, damage spreads to adjacent frequencies, affecting the lower frequencies that are important for speech (Taylor et al, 1965). At this point the person becomes aware of the irreversible hearing damage that has been progressing for years (Clark & Bohne, 1999; Daniel, 2007).

From a functional perspective, noise-induced hearing loss not only leads to reduced hearing sensitivity but also to loss of cochlear frequency tuning and hence impaired frequency selectivity, reduced temporal resolution, and an abnormal increase in loudness sensitivity known as recruitment (Sataloff & Sataloff, 1993; Dobie, 2001). This usually implies poor speech intelligibility in noise (Chung & Mack, 1979; Smoorenburg, 1992; Sliwinska-Kowalska & Davis, 2012). In addition, noise exposure frequently leads to tinnitus (May, 2000; Daniel, 2007), an ongoing ringing or buzzing in the ear.

Both NIHL and tinnitus constitute major limitations in relation to hearing-critical jobs. Hearing-impaired workers have a reduced ability to detect warning signals, to
communicate with coworkers, and to localize sound sources (May, 2000; Suter, 2002). Sound attenuation from the use of personal hearing protective devices in this setting is essential to prevent further damage, but may augment these implications even more (Hetu & Fortin, 1995).

**ISO standards**

The intensity and the duration of noise exposure both determine the degree of NIHL. Higher exposure levels and longer exposure durations cause more severe hearing losses (Taylor et al, 1965; Rösler, 1994; Dobie, 2007), although a very large inter-individual variability in susceptibility to NIHL is observed (Henderson et al, 1993). For a population exposed to noise, this relationship is mathematically described in the widely used international standard ISO-1999 (1990). With this model, the expected noise-induced permanent threshold shift (NIPTS) after a certain exposure to noise can be predicted for each frequency. These effects of noise are considered additive to age-related hearing loss (Dobie, 2001). ISO-1999 also incorporates a database for hearing thresholds as a function of age, in order to predict the total amount of hearing loss for individuals exposed to noise. This mathematical model, indicated as database A is derived from data of an otologically screened non-noise-exposed population, and allows the prediction of hearing threshold levels in relation to age, for males and females seperately (ISO-1999, 1990). Because hearing levels span a range of values, the ISO tables report median audiometric values and percentiles for a given frequency.

**Occupational standards**

Sound intensity is measured as sound pressure level in a logarithmic decibel (dB) scale. Noise exposure measurements are often expressed as dBA, where the ‘A’ represents a filter mimicking the frequency response characteristics of the human auditory system (Dobie, 2001; ANSI S1.42-2001, 2011). The logarithmic scale means that a 3-dB increase in sound level represents a doubling of the sound energy. The 3-dB doubling factor is known as the exchange rate (Dobie, 2001). The equal energy principle of noise exposure states that the amount of hearing loss caused by a sound is directly proportional to the average amount of sound energy received over time. Therefore, a doubling in noise level (i.e. +3 dB) can be offset by halving the permissible exposure duration. For example, an exposure of 88 dBA for 4 hours is considered equivalent to an 8-hour exposure to the same sound at 85 dBA (ISO-1999, 1990; Rabinowitz, 2000).

Occupational safety standards do not allow unprotected exposure to noise levels exceeding a certain limit for 40 hours a week. By exceeding these levels, a person runs a risk of hearing damage. Nelson et al (2005) report that, based on data of the National Institute of Occupational Safety and Health (NIOSH), the theoretical minimum
exposure was defined as 80 dBA; a level found not to have an increased risk of causing hearing loss exceeding 25 dB HL in PTA\textsubscript{1,2,3,4} after 40 years of exposure (Nelson et al., 2005). A limit of 85 dBA was associated with a risk for hearing impairment of 8% and this risk was estimated to be 25% for a 90 dBA limit (NIOSH, 1998).

Specific measures for the prevention and control of exposure to noise in the Netherlands are based on the European Directive 2003/10/EC (EPC, 2003), which was adapted by Dutch national law in 2006 (Staatsblad 56, 2006). This directive states that control measures should be taken to protect workers’ safety and health from the risks arising from noise exposure. These measures should be implemented in a hierarchical order, which in occupational hygiene is called the ‘hierarchy of controls’ (EPC, 2003; Staatsblad 56, 2006). Priority should be given to the reduction of noise exposure at its source, by implementing quieter machinery and equipment, and maintaining them properly. If this is not reasonably possible, technical (e.g. isolation of machines) or organizational measures (e.g. adaptations in the layout of workplace or work schedule) should be taken to reduce the noise exposure level or the duration of the exposure. If the risks arising from noise exposure cannot be prevented by other means, appropriate and properly fitted individual hearing protective devices (HPDs) shall be made available to workers.

The directive defines three exposure values with requirements for action, depending on the equivalent noise level for 8-hour working day:

1) A lower action level of 80 dBA, measured at ear level: employees exposed to noise at or above this level should receive information and training on the risks of exposure to noise, preventive audiometric testing should be provided and individual hearing protectors should be made available to these workers;

2) An upper action level of 85 dBA, measured at ear level: employers are required to reduce noise to intensities below this level, by elimination at its source whenever reasonably practicable or implementing technical and/or organizational measures. Workplaces should be marked with appropriate signs, and employees have the right to have their hearing checked. Individual hearing protectors should be made available to workers and should be used by them;

3) An exposure limit of 87 dBA, measured in the ear canal before the tympanic membrane: when applying this exposure limit, the attenuation provided by individual hearing protection is taken into account. Hence, this exposure level is to be measured in the ear canal before the tympanic membrane, when wearing hearing protection devices. A worker’s noise exposure shall under no circumstances exceed this exposure limit. If so, immediate action should be undertaken.

Hearing ability is tested by audiometric screening. When demonstrable hearing impairment is observed, its most likely cause is determined, and the worker receives
adequate audiological referral if needed (Arbouw, 2006). When the hearing loss is most probably caused by exposure to occupational noise, measures should be taken to prevent further development of NIHL in the individual worker as well as in the specific department of the company. Noise levels should be reassessed and preventative measures should be revised, and employees working in similar circumstances must be given the opportunity to check their hearing (again) (Staatsblad 56, 2006). Moreover, measures to compensate for worker’s functional loss, such as technical or organizational adaptations, should be taken as well.

**Prevention of NIHL**

The vast majority of noise-induced hearing losses is preventable. Primary prevention can be accomplished by eliminating or reducing exposure to excessive noise. Although the hierarchy of controls should be the leading principle for reducing environment levels below the lower action level (EPC, 2003), this is often impractical and costly. Therefore prevention often relies on employee’s use of individual hearing protectors rather than controlling noise exposure at its source (Neitzel & Seixas, 2005). The effective attenuation of HPDs depends on the condition of the material, the fit, and consistency of usage. Discomfort, interference with any other equipment or hinder to communication cause irregular use of HPDs (Suter, 2002; Neitzel & Seixas, 2005). Workers who selectively wear their HPDs experience greatly reduced effective protection as a result of noise exposure received during time of non-use (Gerges et al, 2001). For example, if a hearing protector has an effective attenuation of 20 dBA, and it is worn in an daily ambient noise of 100 dBA for 8 hours, then the worker will be exposed to 80 dBA if the protection is worn 100% of the time. If the same hearing protector is not used during 10% of the working day, the worker will be exposed to a time-weighted average noise level of 90 dBA.

Occupational hearing conservation also incorporates ways for secondary prevention, by means of preventative hearing testing that provides early diagnosis of NIHL. Because of its gradual development NIHL is often unnoticed; listeners are unaware that a hearing disorder is developing until hearing thresholds have dropped markedly in the range of speech frequencies. Early detection of hearing loss is therefore a crucial aspect of hearing conservation; this can increase awareness about the risk for hearing damage caused by noise and can help to prevent further hearing loss development.

Awareness and an objective assessment of hearing ability might induce behavioral changes in order to prevent NIHL. Workers who are demonstrated to have hearing loss after audiometric testing, may be much better motivated to use HPDs properly (Royster, 2003; Hong & Csaszar, 2005). However, construction workers’ use of HPDs is influenced by various factors, such as workers’ perceived benefits and barriers of using HPDs, perceived risk of hearing damage associated with noise exposure, and
safety climate (Melamed et al., 1996; Lusk et al., 1997). Most of these are described in Penders revised health promotion model, a model shown to be useful for explaining the workers’ use of HPDs (Lusk et al., 1997). Some studies have established a direct positive effect of information about the status of an individual’s hearing ability on HPD use (Zohar et al., 1980; Widén et al., 2009), while other studies showed no or only limited effects (Lusk et al., 1998; Lusk et al., 1999; Williams et al., 2004; Edelson et al., 2009). Although the direct association between hearing status and HPD use is not unequivocally proven, knowledge about a worker’s hearing ability can affect different factors in Penders revised health promotion model, such as perceived risk of noise exposure, and benefits of reducing workplace noise, thereby indirectly affecting HPD use (Melamed et al., 1996; Purdy & Williams, 2002; Williams et al., 2004; Azeres & Miguel, 2005).

A literature review by El Dib et al. (2012), showed that interventions to influence the wearing of hearing protection improve the mean use of hearing protective devices compared with non-intervention, especially when they are individually tailored and contain mixed aspects. Hearing testing is a very important aspect of these interventions in hearing conservation; it provides an opportunity to educate workers about NIHL and motivate them to change behaviors regarding hearing protection, it is a starting point for taking (individual) precautionary measures, and it monitors hearing health of the workforce (Royster, 2003).

Although pure-tone air conduction audiometry is the general hearing screening method incorporated in occupational standards, several other possible methods for NIHL screening in occupational health can be considered as well.

**Methods for hearing screening**

**Pure-tone audiometry**

The pure-tone audiogram is considered the gold standard for describing hearing sensitivity (Sataloff & Sataloff, 1993; May, 2000). The audiogram determines the lowest signal level a person can hear over a range of frequencies. The pure-tone hearing thresholds are used to identify and qualify hearing loss, and determine its cause. Screening audiometry involves an assessment of the hearing thresholds using air conduction under headphones only, carried out under specified conditions given in ISO-6189 (ISO, 1983). This audiometric assessment is usually part of a hearing conservation program.

However, pure-tone audiometry does not have perfect precision. Behavioral thresholds vary somewhat from one test to the next, because of tester and patient experience and motivation (Schlauch & Carney, 2012). Clinical test-retest variability,
expressed as standard deviation of the difference, varies from 3 to 6.8 dB depending on frequency (Hétu, 1979; Dobie, 1983; Hall & Lutman, 1999). These values increase somewhat with larger interval lengths (Dobie, 1983).

When audiometric testing is applied in industrial screening programs, the variability may increase even more due to a number of sources of systematic and random errors. These sources may be calibration errors of audiometric equipment, excessive background noise in the testing room, residual TTS at the time of testing, partial or complete obstruction of the external auditory canal (e.g. by cerumen), interfering signals from the test equipment, differences in earphone placement, bias introduced by the tester or the examination procedure, familiarization with the examination procedure and the presence of tinnitus (Hétu, 1979). Many of these error sources can be minimized by careful control of the testing environment, cautiously following the protocol and giving good instructions (Hétu, 1979; Franks, 2001).

Adequate audiometric testing requires a quiet environment with acceptable ambient noise levels during testing, since audiology involves determination of the lowest signal level that a person can hear (Franks, 2001). The maximum permissible ambient noise levels are specified in ISO-6189 (1983). These are rarely achieved without an audiometric soundproof booth, which is not always available in occupational assessment (HSA, 2007). The audiometers must meet ISO standard 8253-1 (1989) and need to be tested for proper function prior to each day’s use, and calibrated according to ISO-389-1 (1998) annually (May, 2000). Employees need to be advised to have a quiet period of ideally 16 hours preceding audiometry, without exposure to either occupational or non-occupational noise, in order to reduce the likelihood of TTS (Franks, 2001). Finally, otoscopic examination should be performed before testing, and findings should be noted. If significant amounts of earwax are present it may be better to advise removal of wax before performing the test (HSA, 2007), as partial obstruction of the ear leads to higher air conductive thresholds (Schlauch & Carney, 2012).

In occupational screening settings these requirements are not easily met, therefore test-retest reliability becomes reduced. Indeed, occupational audiometry is found to be less reliable than clinical audiometry; industrial test-retest variability ranged from 6.7-10.1 dB depending on frequency (Dobie, 1983; Helleman & Dreschler, 2012). As a result, small early threshold shifts for an individual employee cannot easily be distinguished from normal measurement variability (Royster & Royster, 1986), so alternative (or additional) methods were sought to improve early detection of NIHL in occupational health surveillance.

Otoacoustic emissions
One of these proposed alternatives is the measurement of otoacoustic emissions. Healthy ears generate low-level sounds that are by-products of the active, non-linear
properties of the cochlea arising from the OHCs (Kemp, 1978). These sounds are known as otoacoustic emissions (OAEs) and can be recorded by a sensitive microphone inserted in the ear canal (Kemp, 2007). The presence of these emissions provides information on the function of OHCs (Lonsbury-Martin et al, 1995), the structures most vulnerable to high level noise.

The most common application of OAEs is in newborn hearing screening (Lonsbury-Martin et al, 1995; Kemp, 2007), but OAE recording is also suggested to be a sensitive method to screen for NIHL (Lapsley Miller et al, 2006; Lapsley Miller & Marshall, 2007, Marshall et al, 2009). The added value of evoked OAE (EOAE) recording in an occupational audiology environment is that it is a non-invasive objective technique that is not influenced by the patients state of consciousness, it is simple, quick and cost-effective (Chan et al, 2004; Lapsley Miller & Marshall, 2007) and it does not require a sound-proof booth but only a relatively quiet test room.

As OAEs are able to indicate small changes in cochlear function, OAE amplitude reduction can reflect OHC damage due to noise exposure (Sliwinska-Kowalska & Kotylo 2007). EOAEs may provide a more direct measurement of early changes to the inner ear than audiometry (Lapsley Miller & Marshall, 2007), and findings of audiometrically normal-hearing noise-exposed individuals having lower OAEs than non-noise controls suggests that OAEs may show noise-induced changes before they are detectable in the regular pure-tone audiogram (Lapsley Miller & Marshall, 2007). However, evidence for OAE sensitivity to detect so-called preclinical damage is equivocal (Lapsley Miller & Marshall, 2007). Most of the findings are reported by cross-sectional studies (LePage & Murray, 1993; Attias et al, 1998; Desai et al, 1999; Attias et al, 2001), and findings of longitudinal studies could not sufficiently establish this enhanced sensitivity (Engdahl et al, 1996; Seixas et al, 2005; Lapsley-Miller et al, 2004; Konopka et al, 2005; Lapsley Miller et al, 2006; Helleman & Dreschler, 2012). Nevertheless, many studies found reduced OAE amplitudes or absent OAEs as a result of exposure to noise (LePage & Murray 1993; Hotz et al, 1993; Engdahl et al, 1996; Attias et al, 1998; Desai et al, 1999; Attias et al, 2001; Lapsley Miller et al, 2004; Konopka et al, 2005; Lapsley Miller et al, 2006). In addition, high test-retest variability is observed for OAEs, which was lower than for audiometry (Hall & Lutman, 1999; Keppler et al, 2010; Helleman & Dreschler, 2012). However, several aspects limit the application of detecting OAE changes in NIHL screening purposes.

First of all, the high test reliability of OAE measurements can be affected by equipment limitations and methodological issues, such as adequate calibration, the stimulus parameters used and environmental noise (Kemp, 2007; Keppler et al, 2010). Adequate probe placement is highly important for adequate OAE recording, and larger test-retest variability is found after probe refitting (Keppler et al, 2010). In addition, EOAEs are highly dependent on the forward and reverse transmission
through the middle and external ear (Keefe, 2007), and tympanometric pressure has an impact on EOAE amplitudes (Kemp et al, 1990; Marshall et al, 1997). So a reduction in OAE amplitude might also reflect measurement error or a (temporary) conductive hearing loss (Kemp, 2007).

Second, OAEs only reflect OHC function and their presence does neither exclude hearing impairment caused by IHC dysfunction, nor by a retrocochlear dysfunction (Robinette et al, 2007).

Third, and most important, this method is applicable only where reliable OAEs can be recorded. There is a good correlation between OAE sensitivity and hearing threshold up to 30-40 dB HL. Above this level, there is often no recordable OAE (Kemp, 2007). This excludes the investigation of most cases of moderate to severe hearing loss, which is an important limitation for the use of OAE recordings for monitoring purposes. People in hearing conservation programs often have very low emission levels, due to presbyacusis, NIHL or both. It is important to ensure that these low-level emissions are still well above levels of ambient noise (Lapsley Miller et al, 2004). The signal-to-noise ratio (SNR), which refers to the difference between response level and the level of the background noise, can be used as a reliability estimate. Recent investigations in two Dutch hearing conservation programs showed that according to a criterion of SNR ≥ 0 dB, OAEs could not be reliably recorded in 10-45% of the noise-exposed employees investigated, depending on the frequency measured (Helleman et al, 2010; Leensen et al, 2011). For monitoring purposes, an even higher SNR criterion would be more appropriate, as that leaves enough room for deterioration over time (Helleman et al, 2010). However, using a higher SNR as reliability criterion reduces the number of valid OAE data points even more (Helleman et al, 2010; Leensen et al, 2011).

These findings indicate that OAEs can only be used as a reliable monitoring tool for a subset of an industrial population with good baseline hearing. This means that pure-tone audiometry remains necessary when a pre-existing hearing loss is present.

**Speech-in-noise testing**

A speech-in-noise test is a functional hearing test that also may provide a valuable method for NIHL screening. Measuring the ability to understand speech in a background noise has become a commonly used method to quantify everyday communication performance. Difficulty in understanding speech, especially in the presence of background noise, gives rise to the largest number of complaints of sensorineural hearing loss in general (Arlinger, 2003). Since speech reception in noise is highly correlated with the pure-tone average of 2 and 4 kHz (Smoorenburg, 1990; Smoorenburg, 1992), it is often the first problem experienced by subjects with NIHL. Some individuals experience these complaints even in the absence of clinically significant hearing loss in the pure-tone audiogram (Badri et al, 2011; Kumar et al, 2012).
Multiple forms of speech-in-noise testing exist, with different parameters that may influence test results (Theunissen et al, 2009). The most important properties of a speech-in-noise test are the speech material (e.g. sentences, monosyllables, spondees), the type of masking noise (stationary noise, fluctuating noise, multitalker babble etc), and the presentation mode (fixed or adaptive presentation levels). Adaptively presenting a closed set of words in noise, makes speech-in-noise testing very suitable for automated administration, thereby offering opportunities for self-testing. Based on the adaptive up-down procedure introduced by Plomp & Mimpen (1979a), one of the first automated speech-in-noise tests was the National Hearing Test, developed by Smits et al (2004; 2006a), presenting digit-triplets in stationary noise. This fully automatic self-test for screening purposes can be administered by telephone or internet and has been very successful in the Dutch population in general (Smits et al, 2006b). However, the bandwidth of this test was limited to 0.3-3.4 kHz to mimic the telephone network frequencies. Because NIHL predominantly affects the high frequency region, another Dutch broadband online speech-in-noise test was generated; ‘Earcheck’ (Albrecht et al, 2005).

These online tests all measure the speech reception threshold (SRT); the SNR that corresponds to the ratio at which 50% of the speech is correctly understood. Because the test measures a SNR rather than absolute thresholds, this kind of testing is fairly insensitive to poor acoustics due to transduction or background noise (Smits et al, 2004; Culling et al, 2005), placing less demands on the testing environment (Jansen et al, 2010). Moreover, the SRT is not influenced by the absolute presentation level in stationary noise (Plomp & Mimpen, 1979b), requires little calibration, and is very quick (Smits et al, 2004; Culling et al, 2005; Jansen et al, 2010). Finally, speech-in-noise testing is, when presented at a sufficiently high presentation level, insensitive to conductive hearing losses (Plomp, 1986). Due to these factors, speech-in-noise tests can be implemented as an easily accessible and reliable self-screening test that can even be completed in a home setting.

The rapid growth of online screening tests on health status illustrates that the internet is a suitable medium to contact the general public (Koopman et al, 2008). Hence, the greatest advantage of an internet-based self-test for hearing screening is that it offers widespread access to testing (Swanepoel & Hall, 2010), providing a fast way to reach many employees at risk (Stenfelt et al, 2011). As a result, online hearing screening might lead to higher participation rates in hearing conservation. It also offers the opportunity to check hearing ability more frequently e.g. when complaints arise (Koopman et al, 2008), and it can be performed more easily after a period free of occupational noise, reducing possible TTS effects.

Nevertheless, although reduced speech intelligibility in noise was shown for listeners with NIHL (Chung & Mack, 1979; Smoorenburg et al, 1982; Smoorenburg,
the sensitivity of speech-in-noise testing for early NIHL has to be established. Since listeners with NIHL often exhibit (near) normal hearing thresholds in the low to mid frequencies, they can benefit from their preserved hearing when recognizing words in noise (Quist-Hansen et al., 1979). Patients with high-frequency hearing loss above 2 kHz, showed word recognition in stationary noise similar to normal performance (Pekkarinen et al., 1990; Philips et al., 1994). The sensitivity of the online speech-in-noise test Earcheck for NIHL, and its applicability in occupational health will be studied in this thesis.

Outline of this thesis

This thesis studies methods for NIHL screening and monitoring in occupational hearing conservation, as is practiced in the Dutch construction industry.

In the first part of the thesis, the value of the traditional method of pure-tone audiometry in detection of NIHL is investigated, by analysing audiometric data obtained in regular occupational health examinations of a large cohort noise-exposed workers.

Chapter 2 describes a cross-sectional analysis of audiometric thresholds of approximately 30,000 noise-exposed construction workers. Their hearing threshold levels are compared to the ISO-1999 standard, in order to assess excessive hearing loss relative to normal presbyacusis and the correspondence between observed and predicted NIPTS.

Chapter 3 presents the results of a longitudinal analysis of audiometric thresholds of about half of the baseline cohort that obtained a follow-up assessment of hearing. The development of hearing loss over a period of 4 years is investigated, and compared to ISO-1999 predictions for noise and aging. By examining consecutive datasets, the quality of audiometric data collected during screening assessments can be judged as well.

The second part of this thesis aims to develop an alternative approach for NIHL screening. Because an internet application can provide easily accessible hearing screening to a broad public, the application of online speech-in-noise testing for NIHL screening purposes is evaluated and improved.

Chapter 4 evaluates the sensitivity of three versions of a Dutch online speech-in-noise test for detecting NIHL. Since this sensitivity turned out to be rather low, ways to improve its sensitivity, and consequently the applicability for NIHL screening, were investigated.

Chapter 5 describes the results of this investigation of Earcheck adaptations, by concerning homogenization of the speech stimuli and various spectral and temporal
modulations to the masking noise. Sensitivity for NIHL increased extensively when using low-pass filtered masking noise.

The third part of this thesis aims to investigate the value of this newly developed internet-based speech-in-noise test for NIHL screening purposes in hearing conservation. Because of the filtering of the masking noise, the SNR in the high-frequency region is changed, and test results might be affected by uncontrollable parameters of domestic testing. In Chapter 6, these effects are described and investigated.

Finally, Chapter 7 describes the validity of the online speech-in-noise test compared to screening audiometry, and determines the applicability of such a screening test in occupational health.

Chapter 8 presents the general conclusions from this thesis and discusses the relevance of the current findings for occupational hearing conservation. Moreover, some suggestions are given for future research to increase the reliability and applicability of this new testing technique even more.

It should be noted that this thesis is composed of five papers (Chapters 2, and 4 to 7), published or submitted for publication as research paper. This means that these chapters can be read separately, but as a consequence there may be some overlap in the some sections of these chapters.