Clinical measurement of various aspects of hearing impairment and their relation to auditory functioning: the development of an Auditory Profile
van Esch, Thamar

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Hearing impairment involves much more than a reduced sensitivity to soft sounds. In daily life, hearing-impaired listeners also suffer from their distorted processing of audible sounds. For example, people can have difficulties localizing sounds or understanding speech in noisy situations. The degree of these kinds of impairment does not only depend on the ability to detect soft sounds, but also on other aspects of hearing. Nevertheless, in current clinical practice, often only hearing thresholds are measured. The present study investigates possibilities to measure other important aspects of hearing in a clinical setting.

1.1 Hearing

Figure 1.1 shows a schematic overview of the human ear. When a sound wave enters the ear, it travels through the ear canal and vibrates the eardrum (tympanic membrane). The eardrum separates the middle ear from the outer ear and is connected to the cochlea (inner ear) through three
middle ear bones: malleus, incus, and stapes. The vibrating tympanic membrane makes the ossicles move so that the stapes faceplate pushes the inner fluid in the cochlea. Together, the eardrum and ossicles form an impedance transformer: they change the incoming sound pressure wave into a fluid pressure wave. Inside the cochlea, the vibrating fluid induces movement of the basilar membrane. Due to the structure of this membrane, the resonance frequency differs along the length of the membrane. Consequently, the location of maximum movement depends on the frequency of the incoming waveform, creating a tonotopic representation of the sound. On the basilar membrane, the actual sensory organ is situated: the Organ of Corti. This is where the wave is converted into nerve impulses. The Organ of Corti contains two types of receptor cells. The inner hair cells are the actual transduction cells and convert the movement of the basilar membrane into nerve impulses while the outer hair cells play an active role in the amplification
of soft sounds and in sharpening the tonotopic representation. When the inner hair cells are moved, they send nerve impulses through the auditory nerve to the brain, where the sound is perceived.

1.2 Hearing impairment

The degree of a listener’s hearing impairment is expressed by his or her hearing thresholds for a range of frequencies, the pure-tone audiogram. Two main types of hearing impairment are generally distinguished that are classified according to the location of damage: conductive and sensorineural hearing loss.

1.2.1 Conductive hearing loss
A reduced efficiency of the sound transmission through the outer and/or middle ear causes a conductive hearing loss. This can be caused by a variety of reasons such as wax in the ear canal, damage to the eardrum, stiffening of the ossicles, or fluid in the middle ear. It results in an attenuation of sounds reaching the cochlea that is often frequency dependent. Nevertheless, besides reduced intensity of sounds, conductive hearing loss does not generally cause marked perceptive distortions or abnormalities in other aspects of sound perception. Moreover, conductive hearing loss can be reversible.

1.2.2 Sensorineural hearing loss
A sensorineural hearing loss involves damage to the cochlear or to neural structures beyond the cochlear. This type of hearing loss is almost always irreversible and can be caused by exposure to intense sounds, genetic factors, a tumour, and many other causes. Besides a reduced sensitivity for soft sounds, a perceptive hearing loss also causes a variety of changes in the perception of sounds that are well above the detection threshold.

Damage to the outer hair cells is a very common reason for sensorineural hearing loss. The outer hair cells play an active role in the amplification of soft sounds, so a loss of outer hair cells reduces the amplification of
soft sounds. As high-intensity sounds are mostly perceived equally loud or even louder by listeners with a cochlear hearing loss than by normally hearing listeners, the loss of amplification of soft sounds results in a smaller dynamic range and a more rapid growth of the perceived loudness with increasing intensity. This abnormal loudness growth is called loudness recruitment (see e.g. Brand & Hohmann, 2001).

The damage to the outer hair cells also leads to reduced sharpness of frequency tuning in the cochlea and thus to a reduced spectral resolution (e.g. Festen & Plomp, 1983; Dreschler & Plomp, 1985). This means that listeners will be less able to resolve the spectral components in a complex sound.

Finally, a sensorineural hearing loss can also negatively influence the ability to detect variations over time, leading to poorer temporal resolution in listeners with perceptive hearing loss (e.g. Festen & Plomp, 1983; Dreschler & Plomp, 1985).

1.3 Speech perception in noise

In daily life, people have conversations in all kinds of environments. Almost always disturbing sound, usually called noise, is present, for example from other people talking, air conditioning, or traffic. Speech understanding in these noisy situations is challenging, since usually speech and noise signals overlap both in frequency and time. Moreover, speech has very complex time and frequency characteristics, and covers a considerable range of intensities. Even if the speech is above their hearing thresholds, hearing-impaired listeners have much more difficulties understanding speech in noise than normally hearing listeners, especially if the noise is fluctuating in time (e.g. De Laat & Plomp, 1983; Festen & Plomp, 1990; Versfeld & Dreschler, 2002). Interestingly, listeners with nearly identical pure-tone audiograms can have quite different abilities to understand speech in noisy environments. Thus, the reduced ability to understand speech in (fluctuating) noise cannot be explained entirely by reduced sensitivity for soft sounds, but there have to be other causes (e.g. Eisenberg et al, 1995; Bacon et al, 1998; Summers & Molis, 2004). Possible other causes are reduced
spectral and temporal resolution (e.g. Patterson et al, 1982; Glasberg & Moore, 1989; Dreschler & Leeuw, 1990; Noordhoek et al, 2001; George et al, 2006, 2007; Van Esch & Dreschler, 2011), and loudness recruitment (Villchur (1974) and Moore & Glasberg (1993)). Besides that, significant relations between speech perception in noise and outcomes of several cognitive tests have been shown by e.g. Humes (2002), George et al (2007), and Kramer et al (2009).

1.4 Clinical audiological practice

In clinical audiology, hearing rehabilitation is mostly based on the pure-tone audiogram. This means that the advanced signal processing in current hearing aids is based on average processing ability, rather than on the individual capabilities of hearing-impaired individuals. Nevertheless, individual parameters are important to candidature for hearing-aids and for the selection and fine-tuning of specific hearing-aid features. For example, a test of temporal-processing ability might be useful for selecting compression speed for an individual hearing-aid user (Moore, 2008). Also cognitive ability has been suggested to be relevant to candidature for specific hearing-aid amplification regimes (Gatehouse et al, 2003). Moreover, hearing-aid fitting based on individual loudness perception is preferred above a prescriptive fitting according to a study by Pastoors et al (2001), although no significant differences in performance were found between fitting strategies.

Spectral and temporal resolution, loudness recruitment, and cognition are not only potentially important for hearing aid fitting. Based on their relevance for speech perception as described above, they are also of diagnostic importance. For example, measuring these aspects of hearing can provide insight into the underlying causes of for instance a reduced ability to understand speech in noisy situations. Moreover, it can give an indication whether a perceptive hearing loss is caused by damage to the outer hair cells.

In addition to speech perception in noise, spatial hearing is extremely important for auditory functioning in HI listeners (Noble et al, 1995;
Kramer et al, 1998; Gatehouse & Noble 2004). Spatial hearing has a large influence on the degree of handicap experienced by HI persons (Kramer et al, 1998; Gatehouse & Noble, 2004; Noble & Gatehouse, 2004) and it is known that listeners with asymmetric hearing loss are more disabled in spatial hearing than listeners with symmetric hearing losses (Noble & Gatehouse, 2004).

Furthermore, there is need for a measure of listening-effort in order to be able to differentiate ease-of-listening at supra-threshold levels from speech intelligibility at the speech recognition threshold.

These aspects of hearing are widely investigated in research settings using many different, often time-consuming, tests. There are very few applications in clinical audiology. In fact, only few methods are available to measure these aspects in a standardized, clinically applicable way. The goal of the present thesis is to develop a battery of standardized tests that are clinically applicable and that measure these aspects of hearing.

1.5 Outline of this thesis

This thesis focuses on clinically applicable tests that could complement the pure-tone audiogram. The clinical usability and relevance of these specific tests for speech perception or broader auditory functioning is investigated. The end result is a test battery that could serve as a standard in extensive diagnostics or in audiological research. More specifically, the test battery can be used for research on the consequences of certain individual hearing capacities for hearing-aid fitting. This may stimulate the future application this test battery for clinical auditory rehabilitation.

We will start with two chapters that focus on spectral and temporal resolution measurements. The last two chapters have a broader scope and present the composition and results of the preliminary Auditory Profile test battery. The selected spectral and temporal resolution test from the first chapters is part of this test battery.

**Chapter 2** investigates and compares two clinically applicable tests (‘tone test’ and ‘sweep test’) that measure both spectral and temporal resolution simultaneously. Test-retest reliabilities and learning effects are ex-
amined in normally hearing and hearing-impaired listeners. Next, results from the tone test and the sweep test are compared to results from conventional spectral and temporal-resolution tests and to speech perception in noise scores. We conclude that the tone test (after certain modifications) is a fast and reliable test that is suitable for measuring spectral and temporal resolution in a clinical setting.

In Chapter 3 we consider many more aspects of auditory communication, as in this chapter the preliminary Auditory Profile test battery is presented. This test battery includes measures of loudness perception, listening effort, speech perception, spectral and temporal resolution, spatial hearing, self-reported disability and handicap, and cognition. These tests are evaluated in a multi-centre study with five centres from four different countries, with over one hundred listeners (normally hearing and hearing-impaired) included. Clinical applicability and comparability across different centres are investigated for each test. We conclude that most tests are clinically applicable and applicable in the four different languages, but that for hearing-impaired listeners differences between test materials have to be taken into account for the language-dependent tests, even after a baseline correction.

Results from the multi-centre study as presented in Chapter 3 are further investigated in Chapters 4 and 5.

In Chapter 4, relations between results from the different tests are examined, with a focus on the relevance for speech perception in noise, in addition to the pure-tone audiogram and age. We conclude that spectral and temporal resolution are the most important factors for explaining speech perception in noise.

Results from different tests on spatial hearing are compared to subjective binaural functioning in Chapter 5. We found that the MAA test and the spatial SRT benefit test are indicative measures for self-reported binaural functioning. The MAA test best represents self-reported localization, while the SRT benefit test was found to be the most important for self-reported listening to speech in spatial situations.

Finally, we conclude in Chapter 6 with a summary and final discussion of Chapters 2 to 5.

It should be noted that this thesis is composed from four papers (chapters 2 to 5) that are published or submitted to be published in scientific
journals. This means that these chapters can be read independently, but also that there may be some overlap in the Introduction and Methods sections of these chapters.