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Digital hearing aids and future directions for hearing aids

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Abstract. *Digital hearing aids and future directions for hearing aids.* In recent years many technical evolutions have been applied in hearing aids. In this paper differences between analog, programmable and fully digital hearing aids, the basic and supplementary functions of a hearing aid, and some important issues and future directions for digital hearing aids will be mentioned.

Introduction

The first fully digital hearing aid was only introduced in 1995 (Widex Senso) and the market share of digital devices is ever increasing. The differences between analog, programmable and fully digital hearing aids can be made clear using schematic representations (see figure). Whereas any hearing aid consists of a microphone system and a receiver part as in- and output of the device, the main differences are present in the functionalities. As such, an analog hearing aid has only a few controls. These are potentiometers (for example for some spectral adjustment of the fitting and for setting limiter levels) or switches. Programmable hearing aids use digital control circuits, usually more in number and precision than in analog hearing aids, although the acoustical signal path is fully analog. In digital hearing aids the input signal is converted from the analog to the digital domain, then processed digitally and finally converted to the analog domain again to the receiver or telephone output. The programmable and fully digital aids allow remote control and multiple listening programs. Multiple programs may be needed because different acoustical environments may necessitate different hearing aid settings for optimal listening. Furthermore, digital hearing aids allow flexible fitting (via software), more complex processing (for example in more than 10 frequency bands), several processing schemes and allow decision making routines in sensing the acoustical environment. Although the size and power consumption of digital circuits is reducing at a faster rate than is the case for analog circuits, digital hearing aids are considerably more expensive than analog hearing aids. The latter is a major disadvantage of digital hearing aids.

The basic functions of a hearing aid are firstly the amplification to lower the higher hearing thresholds of the hearing impaired and secondly compression of the acoustical domain. The latter is necessary to limit the maximal output level (compression limiter) and/or to take into account the reduced dynamic range of the impaired ear (dynamic range compression). The relatively similar uncomfortable loudness levels of a lot of sensorineural hearing impaired listeners are pivotal for this. Besides these basic functions of a hearing aid a lot of additional or supplementary functions are present in modern hearing aids. The filtering of the input signal in multiple channels that can be processed separately or independently, the application of multiple listening programs (comfort, intelligibility, ...), noise reduction strategies (microphone systems, adaptive filtering algorithms, ...), feedback suppression which may especially be important for the more severe hearing losses, automatic sound scenario sensing for automatic determination of best signal processing and remote control are some of these additional functions. Although they are not (yet) basic, some of these aspects may be very important for hearing impaired subjects. Contrary to the basic functions, these additional functions can more easily, more accurately and some even exclusively be implemented in digital hearing aids.

In what follows some important issues and future directions will be addressed.

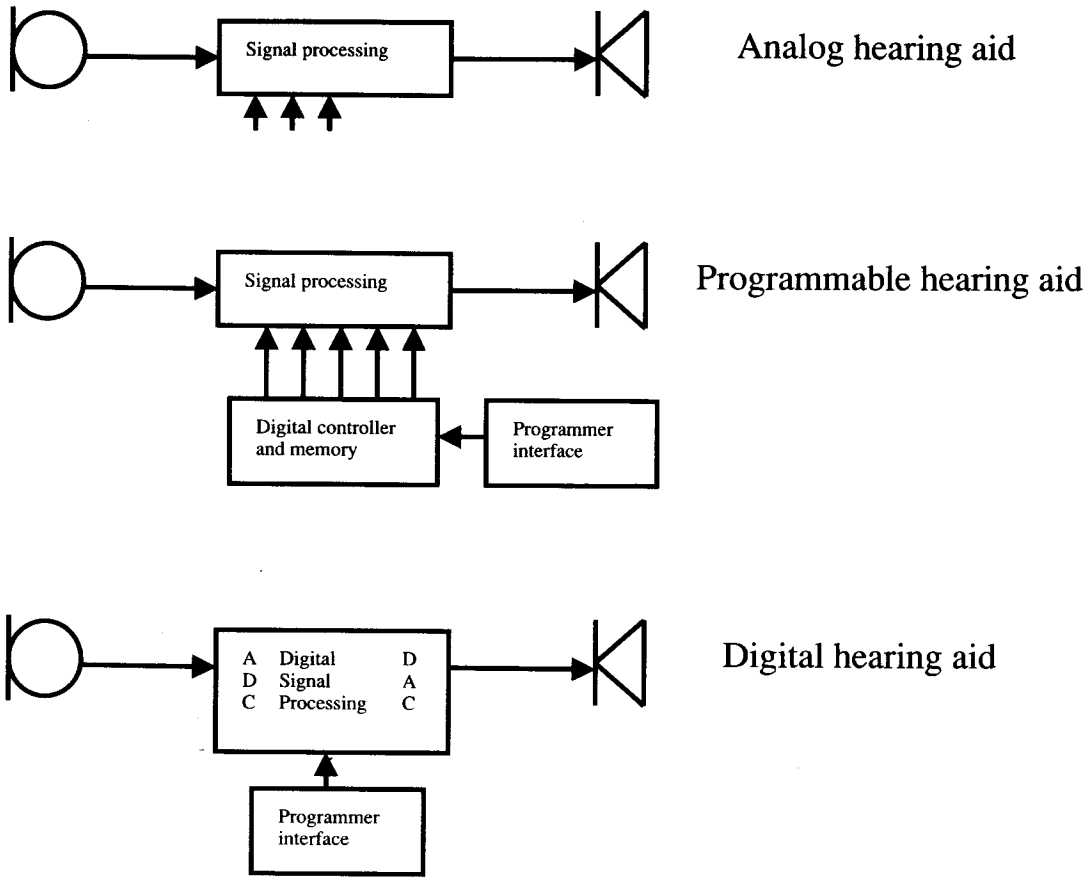

Fig. 1
Block diagrams of an analog, a programmable and a digital hearing aid

Spatial awareness and directional hearing

The spatial awareness of hearing impaired people has in most cases escaped important attention in hearing aid applications and evaluations. The human directional hearing abilities of a sound source in the horizontal plane are based on the interaural level differences (ILD) and interaural time differences (ITD) of the sound between the two ears. Additionally, the pinna introduces a front-back differentiation due to different acoustical transfer functions at high frequencies. These differences allow spatial differentiation of sounds. The ILDs (also head shadow effect) can be up to 15 dB at high frequencies and ITDs for an adult head are about 650 (s for sounds arriving at 90° relative to the frontal direction.

It is certainly questionable that these cues are preserved in hearing aids. The 2 hearing aids in bilateral fittings are acting independently. This may induce different activations of the compression systems in the left and right hearing aid. Furthermore, processing time differences for different fittings of both digital hearing aids can be easily of the same order of magnitude as ITDs. Directional hearing and thus spatial awareness for hearing aid users may be considerably reduced. Some studies have even shown that in some cases directional hearing using 2 hearing aids can be worse than without hearing aids (1) ! So, directional hearing is an important issue for digital hearing aids.

From large scale questionnaire studies in the US (with thousands of subjects collaborating) we have learned that from all the different technical evolutions that have become available in digital hearing aids, it is mainly the noise reduction or speech enhancement in noisy environments that has made a big difference for hearing aid users in real life (2-4). Partly

based on the more technical perspective, however, we have not always been asking the right questions to hearing impaired people in benefit-assessment procedures. Moreover, good directional hearing tests are clinically not routinely done and are not straightforwardly correlated with spatial awareness, partly because of the test set-ups used. The spatial awareness issue has partly escaped attention. Nevertheless, every clinical audiologist can inform you that the spatial awareness is a very important issue for hearing impaired people.

Recently, Stuart Gatehouse addressed these aspects and included spatial aspects of hearing such as distance, movement and selective attention in the assessment of the benefit of hearing aids. He developed the SSQ (Speech, Spatial, Quality of hearing) assessment instrument that consists of 49 questions that are administered in an interview with the hearing aid user and the evaluation is by means of a ruler-like response between 0 and 10 (5-7). The inclusion of aspects such as "can you lateralize a talker to the left or to the right" and "can you identify lateral movement of a vehicle" are representations of the spatial awareness of the hearing aid user and are original and relatively new in well-structured formal assessment procedures. From his research with these tools in which large numbers of hearing aid users were questioned on different auditory situations and scenarios, a multidimensional statistical analysis revealed that the speech intelligibility in noisy environments AND the spatial awareness are the most important dimensions for hearing impaired people using hearing aids (6). Although clinical audiologists in the field may know this for a long time and observe daily the importance of the spatial awareness, we have not had the right tools yet to assess clinically the spatial hearing dimension. This is in contrast with the speech understanding in noise where speech audiometric tools for assessment are available. Gatehouse's approach is a very good attempt to factor the benefit from wearing hearing aids along the spatial awareness dimension.

Signal processing adapted to the auditory needs of the hearing impaired

The fitting of hearing aids is mainly based on audiometric measures of hearing thresholds and of uncomfortable loudness levels at a set of frequencies (mostly octaves apart). These parameters determine the amplification (the audibility of the sounds) and the compression to be applied in the hearing device, which are the basic functions of hearing aids.

However, in recent years auditory research has pointed to some specifications related to individual hearing impairments and important for consideration in hearing aid fitting. Tammo Houtgast and his group have recently carried out extensive batteries of psychophysical tests with large numbers of sensorineural hearing impaired subjects. The psychophysical measurements were meant to quantify the spectral and temporal resolutions or abilities of the subjects (8). The data showed that about 50% of the tested hearing impaired subjects have no supra-threshold deficit. This means that restoring the audibility of sounds in these subjects is most important. The other 50% of the subjects do also have supra-threshold deficits in addition to the audibility-issue : about 30% have mainly spectral deficiencies and about 20% have significant temporal resolution deficits (9-11).

Brian Moore and his group are investigating methods to quantify so-called "dead regions" or "lacunae" along the tonotopical axis (12-14).

Results of these studies suggest more individually adjusted hearing aid fittings.

These more-than-just-audibility deficits have not seriously been addressed yet in hearing aids, but software flexibility of future digital hearing aids may allow taking into account these supra-threshold aspects in the adaptation of the signal processing to the needs of the hearing impaired individual. However, we will need clinical tools, i.e. time-efficient psychophysical tests that can be administered easily in a clinical environment, to specify the deficits and to apply in the fitting of hearing aids.

Better fitting of hearing aids in young children

Since 1998 a general neonatal hearing screening program, using the Algo automatic brainstem audiometry, has been organized in Flanders and Brussels. The coverage is about 96% of all newborns. This project is very successful. The yes-no answer about the occurrence of an auditory impairment of more than about 40 dB triggers further steps along the path of rehabilitation. Auditory rehabilitation centers for children are being confronted in recent years with the significantly reduced age of hearing aid fitting which is a prerequisite for early

sound reception and improved speech- and language acquisition (15, 16). This project has triggered an increased interest for aspects concerning fitting hearing aids in these very young children. Urgent questions about fitting these young ears and further more specific diagnostics need to be addressed. Firstly, the variability and change with aging of the ear canals in very young children needs consideration. The application of probe-microphone measurements, the reliability of real-ear-to-coupler (RECD) values and tests with different earmolds are important issues. Secondly, click brainstem response audiometry is the most-widely applied diagnostic procedure for objective threshold estimation, but more frequency specific threshold information is necessary for adequate fitting of hearing aids in these young children.

Recently, increased attention has gone to objective frequency-specific hearing threshold measurement (17, 18). Steady state evoked responses may yield this frequency-specific information. At K.U.Leuven steady state evoked potentials are being studied for these purposes. Based on tests with normal hearing and hearing impaired adults, a clinical protocol has been developed and evaluated for children at ages below 8 months. In about 45 minutes we are able to obtain thresholds in the 2 ears at 4 octave frequencies simultaneously at an accuracy of 10 dB (19, 20). This additional diagnostic information is used for more adequate hearing aid fitting in these very young children. This threshold information can more easily be incorporated in digital hearing aids.

Improvement of speech understanding in noisy environments

The reduced speech understanding in noisy or multi-speaker environments is one of the main problems of hearing aid users. Multimicrophone systems and algorithmic approaches have been suggested for these purposes and some even realized in hearing aids. Based on a single microphone input the separation of desired and interfering sounds is impossible when the spectral and temporal characteristics are similar. By using two microphones spatial information can be used. The latter approach has already for a long time been applied in directional microphones (where 2 inputs are mechanically combined to obtain a non-uniform directional pattern) and since the introduction of the Phonak zoom instruments about seven years ago also by combining the outputs of two omnidirectional microphones. In this way the user can switch between fixed patterns of directionality. Interfering sound sources from the sides or from the back hemisphere can successfully be attenuated in critical speech reception scenarios. More recently, adaptive signal processing has been added to two microphone configurations. Principally, this allows the spatially-selective suppression of jammer sources, even with changing positions. The first adaptive systems have been implemented in commercial digital hearing aids (Phonak Claro, GN ReSound Canta). At K.U.Leuven we are developing next generation adaptive signal processing strategies for enhanced speech-in-noise understanding. One of these schemes is an adaptive beamformer based on generalized sidelobe canceling (21) and has been tested with normal hearing, hearing impaired and cochlear implant subjects (22- 24). Improvements in speech-in-noise of about 10 dB have been obtained for a single speech-like jammer source in a living-room-like listening environment. Of course, all speech-in-noise enhancements are dependent on the acoustical conditions and improvements will be lower for large numbers of independent interfering sources. This is linked to the limited input degrees of freedom (number of microphones). More elaborate and robust strategies are presently being worked out based on optimal filtering (25, 26).

The noise suppression algorithms are solely applied in connection with digital hearing aids. The most recent digital signal processors (to be) used in hearing aids are flexible and powerful (arithmetic power) enough for inclusion of more elaborate noise reduction strategies.

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