European Research Council

ERC Advanced Grant 2011
Research proposal (Part B1)

Objective Assessment of Hearing Aid Quality on the Basis of Perceptual Modelling

Principal Investigator (PI)	dr. John G. Beerends
PI's host institution	TNO, Nederlandse Organisatie voor Toegepast Natuurwetenschappelijk Onderzoek (Netherlands Organization for Applied Research)
Proposal full title	Objective Assessment of Hearing Aid Quality on the Basis of Perceptual Modelling
Proposal short name	Assessment of Hearing Aid Quality (AHAQ)
Proposal duration	60 months

Proposal summary

The number of people suffering from a form of hearing impairment is rapidly increasing. In the last decades many claims have been made that new digital hearing aids will lead to a significant improvement in restoring damaged hearing. However, none of the manufacturers has ever been able to prove scientifically that a big leap forward in restoring normal hearing has been made. Small improvements have been made and verified by subjective testing. Each year new types of hearing aids are being introduced with prices that can go far beyond 1000 Euro per ear. Testing these new types and tracking the quality improvements is nearly impossible by subjective testing. Having an objective measurement method for assessing the quality of hearing aids would allow making significant progress in both the development and optimization of hearing aids, including optimization of personalized fittings.

In this ERC project I propose to develop a perceptual hearing aid quality model for the objective assessment of the sound quality of hearing aids using two different approaches. The first approach is based on perceptual models developed in the field of telecommunication for measuring speech and audio quality (referred to as the *direct perceptual* approach). The second approach uses the basic ideas from advanced bio-physical and psycho-physical models as developed in the last decade (*basic* approach).

The *direct perceptual approach* starts with the models as standardized by the International Telecommunication Union (ITU), the first one (Rec. P.861, 1996) being developed, patented and published by Beerends and Stemerdink in the early nineties and its follow ups (P.862, 2001 and P.863, 2011), developed, patented and published by Beerends et al. The *basic* approach uses models as found in a wide variety of papers complemented with the perceptual and cognitive modelling of the ITU standards that have proven to significantly improve the correlation between subjective and objective quality measurements.

In a first limited context I have shown that the basic ideas developed in the telecommunication industry can be applied to measuring hearing aid quality but unfortunately severe problems popped up during this first development. This ERC project is focussed on solving these problems in five work packages. In the first work package subjects that have a similar hearing loss are used to develop a speech quality measure. In the second work package an extension is made towards speech intelligibility. The third and fourth work packages extend the findings towards a wide set of hearing loss profiles and towards other signals then speech, i.e. music and background signals. Finally an extension is developed that takes into account binaural effects. The results will indicate whether a single model is possible or that a context dependent modelling is necessary. The final model(s) will not only allow checking and optimizing hearing aid quality but also to develop new hearing aids with better sound quality in shorter time at lower costs. Possibly certain types of signal processing will be discovered that lead to ground braking improvements in the development of hearing aids.

Section 1 (B1)
a. Scientific Leadership Profile

John Beerends made his first innovation in 1983, while being an MSc student in physics, in the field of sound perception by applying group theoretical arguments to a loudspeaker design. This idea was patented by a subsidy of the Dutch Ministry of Economic Affairs and won a prize of DFl 45000 by Job Creation.

During his PhD (1984-1989, Technical University Eindhoven), which was published in the Journal of the Acoustical Society of America (JASA), he developed a new pitch meter that was patented by Philips. In this period he also worked on a psycho-acoustically optimized loudspeaker system for the Dutch loudspeaker manufacturer BNS. The system was commercially introduced at the Dutch consumer exhibition FIRATO in 1988.

In 1989 he joined the KPN Research Laboratory in Leidschendam where he worked on audio and video quality assessment, audio-visual interaction, and on audio coding (speech and music). This work led to several patents and measurement methods for objective, perceptual, assessment of audio and video quality. Together with Jan Stemerdink **he developed the first world wide accepted standard for the objective assessment of speech quality called PSQM** (Perceptual Speech Quality Measure, www.psqm.com, ITU Recommendation P.861, 1996) [5], [6] [BeP1..4] dealing with the quality of telephone-band speech codecs. They also co-developed PEAQ (Perceptual Evaluation of Audio Quality, www.peaq.org, ITU Rec. BS.1387, 2001) [7], [8], [9] that deals with measuring the quality of music codecs. Together with Andries Hekstra **he developed the perceptual model of the follow up standard of PSQM, called PESQ** (Perceptual Evaluation of Speech Quality, www.pesq.org, ITU Rec. P.862, 2001) [10], [11], [12] [BeP6]. They also co-developed a measurement method for objective, perceptual, assessment of video quality PEVQ (Perceptual Evaluation of Video Quality, ITU Rec. J.247, 2008) [BeJ3].

In January 2003 John joined TNO which took over the research activities from KPN. At TNO he focussed on the degradation decomposition [BeJ5], speech intelligibility [BeJ6], tone language quality [BeJ7], (super)wideband speech quality [BeJ8], hearing aid quality, videophone quality. His latest achievement is a new advanced psycho-acoustic model that was combined with an advanced time de-warping algorithm developed by OPTICOM, the commercial partner of TNO and KPN. This model showed best performance in an ITU benchmark and was subsequently integrated with the next best proposal from SwissQual. The final model was accepted in 2011 under the name POLQA (Perceptual Objective Listening Quality Assessment, www.polqa.info, ITU Rec. P.863). **POLQA is the follow up standard of PESQ and uses the perceptual modelling as developed by Beerends [BeJ5] [BeJ8], [13].**

John Beerends is the (co-) author of more than 60 papers/ITU contributions and 25 patents on various topics of which the most important ones are pitch measurement, speech/audio quality, speech intelligibility, video quality and data chirping. In 2002 he received an AES fellowship award for his work on audio and video quality measurement and in 2003 a best paper award for the joint publication on PEAQ.

John Beerends has carried out many commercial assignments for TNO over the last seven years; most of this work is not available in the public domain. His first ideas on applying the measurement approach developed for the telecommunication industry to the hearing aid industry were made public in the Journal of the AES [25].

During the 20 years of development of quality assessment algorithms John has supervised many students in the field, many of them still working in related areas, examples are:
Deborah Ebem (2009-2010) Dept. of Computer Science, University of Nigeria, Nsukka. Enugu State, Nigeria, currently working as a University lecturer in Nigeria JAES paper [BeJ7].
Bartosz Busz (2006-2007), Wroclaw University of Technology Poland, currently working for Nokia Siemens Networks in Poland, JAES paper [BeJ5].
Paul Oudshoorn (2004-2005), Technical University Delft, currently manager at Accenture Technology Consulting, JAES paper [BeJ5].
Ronald Appel (1999-2001), Technical University Delft, currently Head of Engineering at Sonion Vietnam, JAES paper [BeJ2].

Section 1 (B1)
b. Curriculum Vitae

Education

1970 - 1975 Study electronics, engineering degree in 1975 (Ing), Polytechnic Institute, The Hague.

1978 - 1984 Study physics and mathematics, university degree in 1984 (MSc), University Leiden.

1984 - 1989 PhD Research position at the Institute for Perception Research, Technical University Eindhoven. Pitch perception research funded by the Netherlands Organization for Scientific Research, foundation Psychon.
PhD in 1989 "Pitches of simultaneous complex tones", promotor prof. dr. H. Bouma, co-promotor prof. dr. A. J. M. Houtsma.
Publications in the JASA.
Patent pitch meter by Philips International B.V., 9020044007 Europe; 487462 and 5321636 USA, 45984/90 Japan.

Professional activities

1975 -1978 Various jobs as an electro technical engineer through employment agencies (e.g. super tanker guidance for the Europort Rotterdam at the Control and Information Centre Hook of Holland).

1982 -1983 Private research into the perception of mode distortion resulting in a patent subsidized by the Dutch Ministry of Economic Affairs, Patent office Arnold and Siedsma, The Hague.

1987 - 1989 Development of the Energetic Diffuse Field System for the loudspeaker firm Vandenberghe B.V., Loon op Zand. Commercial introduction, August 1988 at the consumer electronics exhibition FIRATO, Amsterdam.

1989 – 2002 Technical scientific researcher at KPN Research, Leidschendam.
Audio/video quality measurement, echo perception, audio coding (speech and music).
Development of PSQM, PESQ (ITU-T Rec. P.861 and P.862), PEAQ (ITU-R Rec. BS.1387), PEVQ (ITU-T rec. J.247).
Publications in the JAES, IEEE and ITU. Many KPN registered patents on speech coding, audio/video quality measurement.

2003 - Present Technical scientific researcher at TNO Delft.
Speech intelligibility, degradation decomposition, tone language quality, (super)wideband speech quality, hearing aid quality, videophone quality, data chirping and web browse quality measurements. Development of POLQA (ITU-T Rec. P.863), web-browsing opinion model (ITU-T Rec. G.1030).
Publications in the JAES and ITU. TNO and KPN registered patents on speech quality measurement, degradation decomposition, intelligibility measurement, data chirp technique.

Awards and prizes

1983 Second place in an idea contest by Job Creation (June 1983), The Hague. Awarded with 45000 guilders for the commercial development of the patent “Loudspeaker enclosure,” Patent application 8300331, The Netherlands, Patent office Arnold en Siedsma, The Hague (January 1983).

1994 Diana prize for best KPN research project, the development of PSQM (ITU-T Rec. P.861).

2002 Audio Engineering Society fellowship award for his work on audio and video quality.

2003 Best paper award from the Journal of the Audio Engineering Society for the joint publication on PEAQ (ITU-R Rec. BS.1387).

Funding

1982	Funding for patent application by the Dutch Ministry of Economic Affairs on the topic of loudspeaker mode distortion while being an MSc student in physics. Patent office Arnold and Siedsma, The Hague.
2003-present	Direct commercial funding by several companies, total amount over 3.5 M€.
2006-2009	Funding by the Dutch Ministry of Economic affairs (800 k€) with co-financing by KPN, for the project "Speech quality, intelligibility and speech degradation decomposition", leading to ITU-T Rec. P.863 (POLQA).

Currently John has no open funding application for his research activities.

Reviewer

- Journal of the Audio Engineering Society (regularly)
- IEEE Transactions on Audio, Speech and Language Processing (regularly)
- IEEE Signal Processing Letters (ad hoc)
- Journal of the Acoustical Society of America (ad hoc)
- EURASIP Journal on Applied Signal Processing (ad hoc)

Co-operations

1989-1996	ir. Jan Stemerdink (KPN Research, Nokia, Ericsson, Twente Institute for Wireless and Mobile Communications), development of the first world standard for measuring speech quality PSQM (ITU-T Rec. P.861) and co-development of the first world standard for measuring the quality of music codecs PEAQ (ITU-R BS.1387).
1992-2009	dr. ir. Andries Hekstra (KPN Research, Philips, NXP), development of the perceptual model of the second and third world standard for measuring speech quality PESQ (ITU-T Rec. P.862) and POLQA (ITU-T Rec. P.863), co-development of PEVQ (ITU-T Rec. J.247).
1995-present	OPTICOM (Germany) co-development of speech, audio and video quality assessment systems, commercial partner of both KPN and TNO who also takes care of the licensing of the granted KPN and TNO patents.
1999-2001	Psytechnics (UK), co-development of the second world standard for measuring speech quality PESQ (ITU-T Rec. P.862).
2005-2007	dr. Rainer Huber, HörTech (Germany), co-development of the first objective hearing aid quality assessment methods.
2002-2011	ir. Christian Schmidmer, OPTICOM (Germany), co-development of the third world standard for measuring speech quality POLQA (ITU-T Rec. P.863).

During his research career John supervised more than 20 students of which a number of them made significant contributions in the world of perceptual measurements [BeJ2], [BeJ5], [BeJ7] (see B1 a.) John is the (co-) author of more than 60 papers/ITU contributions and 25 patents.

AES	=	Audio Engineering Society
IEEE	=	Institute of Electrical and Electronics Engineers
ITU	=	International Telecommunication Union
ITU-T	=	International Telecommunication Union – Telecom sector
ITU-R	=	International Telecommunication Union – Radio sector
JASA	=	Journal of the Acoustical Society of America
JAES	=	Journal of the Audio Engineering Society
KPN	=	Koninklijke PTT Nederland (Royal Dutch Telecom)
TNO	=	Nederlandse Organisatie voor Toegepast Natuurwetenschappelijk Onderzoek (Netherlands Organization for Applied Research)

Section 1 (B1)

c. 10-Year Track-Record

[BeJ] = Journal paper, [BeC] = Conference paper, [BeS] = Standardization contribution, [BeP] = Patent

Hirsch Number = 17, most cited paper is [7] from 1992 with a citation score of 291 (QuadSearch).

[BeJ1] J. G. Beerends, A. P. Hekstra, A. W. Rix and M. P. Hollier, “PESQ, the new ITU standard for objective measurement of perceived speech quality, Part II - Perceptual model,” J. Audio Eng. Soc., vol. 50, pp. 765-778 (2002). (citation score 80)

[BeJ2] S. R. Appel and J. G. Beerends, “On the quality of hearing one’s own voice,” J. Audio Eng. Soc., vol. 50, pp. 237-248 (2002). (citation score 17)

[BeJ3] A. P. Hekstra, J. G. Beerends, D. Ledermann, F. E. de Caluwe, S Kohler, R. H. Koenen, S. Rihs, M. Ehrsam, D. Schlauss, “PVQM - A Perceptual Video Quality Measure,” Signal Processing Image Communication, vol. 17, pp. 781-798” (2002). (citation score 52)

[BeJ4] A. W. Rix, J. G. Beerends, Doh-Suk Kim, P. Kroon, IEEE and O. Ghitza, “Objective assessment of speech and audio quality - technology and applications,” IEEE Transactions on Speech and Audio Processing, vol 14, pp. 1890-1901 (2006). (citation score 43)

[BeJ5] J. G. Beerends, B. P. Busz, P. Oudshoorn, J. M. Van Vugt, O. K. Ahmed, O. A. Niamut, “Degradation Decomposition of the Perceived Quality of Speech Signals on the Basis of a Perceptual Modeling Approach,” J. Audio Eng. Soc., vol. 55, pp. 1059-1076 (2007). (citation score 3)

[BeJ6] J. G. Beerends, R. A. van Buuren, J. M. Van Vugt, J. A. Verhave, “Objective Speech Intelligibility Measurement on the Basis of Natural Speech in Combination with Perceptual Modeling,” J. Audio Eng. Soc., vol. 57, pp. 299-308 (2009).

[BeJ7] D. U. Ebem, J. G. Beerends, C. Schmidmer, J. M . Van Vugt and R. E. Kooij, “The Impact of Tone Language on Measuring Speech Quality,” J. Audio Eng. Soc., submitted 2010 May.

[BeJ8] J. G. Beerends, C. Schmidmer, J. Berger, M. Obermann, R. Ullman, J. Pomy, “Perceptual Objective Listening Quality Assessment (POLQA), the new ITU standard for end-to-end speech quality measurement” J. Audio Eng. Soc., submitted 2011 Feb.

[BeC1] J. G. Beerends and J. M. van Vugt, “An Extension of PESQ for Assessing the Quality of Speech Degraded by Severe Time Clipping and Linear Frequency Response Distortions,” Joint conference of the German and French acoustical society, DAGA 2004, Strasbourg 2004.

[BeC2] J. G. Beerends, E. Larsen, N. Lyer, J. M. van Vugt, “Measurement of speech intelligibility based on the PESQ approach,” Proceedings of the Workshop Measurement of Speech and Audio Quality in Networks (MESAQIN), Prague, Czech Republic 2004.

[BeC3] J. G. Beerends, J. Krebber, R. Huber, K. Eneman, H. Luts, "Speech quality measurement for the hearing impaired on the basis of PESQ," 124th Convention of the Audio Engineering Society, Convention Paper 7404 Amsterdam, The Netherlands 2008.

[BeC4] J. G. Beerends, R. A. van Buuren, J. M. Van Vugt and J.A. Verhave, “PESQ Based Speech Intelligibility Measurement,” Joint conference of the German and Dutch acoustical society, DAGA 2009, Rotterdam, The Netherlands 2009.

[BeC5] J. G. Beerends, “Measuring the quality of speech and music signals, from philosophy to practical algorithm”, QoMEX, Quality of Multimedia Experience conference, Trondheim, Norway 2010.

[BeS1] J. G. Beerends and S. R. Appel, “Proposed draft recommendation on the perceptual echo and sidetone quality measure (PESQM), an objective method for talking quality assessment,” ITU-T Study Group 12, White contribution COM 12-110, 2000.

[BeS2] J. G. Beerends, A. W. Rix, A. P. Hekstra, M. P. Hollier, “Draft new recommendation P.862: Perceptual Evaluation of Speech Quality (PESQ), an objective method for end-to-end speech quality assessment of narrowband telephone networks and speech codecs,” ITU-T Study Group 12, White contribution COM 12-5, 2001.

[BeS3] J. G. Beerends, “A subjective/objective test protocol for determining the conversational quality of a voice link,” ITU-T Study Group 12, White contribution COM 12-55, 2003.

[BeS4] J. G. Beerends, “Extending P.862 PESQ for assessing speech intelligibility,” ITU-T Study Group 12, White contribution COM 12-C2, 2004.

[BeS5] J. G. Beerends, P. C. H. Oudshoorn and J. M. van Vugt, "Speech degradation decomposition using a P.862 PESQ based approach," ITU-T Study Group 12, White contribution COM 12-C4 2004.

[BeS6] J. G. Beerends and J. M. van Vugt, "Modelling the impact of linear frequency response distortions using a P.862 PESQ based approach," ITU-T Study Group 12, White contribution COM 12-C20 2005.

[BeS7] J. G. Beerends, J. M. van Vugt and J. Jensen, "Predicting listening effort with noise suppressors on the basis of PESQ," ITU-T Study Group 12, White contribution COM 12-C25, 2006.

[BeS8] J. G. Beerends, J. Krebber and R. Huber, "Speech quality measurement for the hearing impaired on the basis of PESQ," ITU-T Study Group 12, White contribution COM 12-C79, 2007.

[BeP1] J. G. Beerends, "Signal quality determining device and method," International patent application 402068; PCT EP96/01102; International patent publication WO 96/28953, September 1996; USA Patent 6064946, EP 0815707, May 2000; KPN N.V. (AKB schaler)

[BeP2] J. G. Beerends, "Signal quality determining device and method," International patent application 402223; PCT EP96/01143; International patent publication WO 96/28950, September 1996; USA Patent 6041294, EP 0815705, May 2000; KPN N.V. (AKB schaler 2, internal noise)

[BeP3] J. G. Beerends, "Device and method for signal quality determination," International patent application 402279; PCT EP0945045, International patent publication WO 98/26633, EP 0945045, June 1998; Koninklijke PTT Nederland N.V. (speech gsm) \

[BeP4] J. G. Beerends, "Signal quality determining device and method," International patent application 402211; International patent publication WO 96/28952, September 1996; USA Patent 6064966, May 2000; KPN N.V. (audio complexity)

[BeP5] J. G. Beerends, "Measuring the perceptual quality of speech signals including echo disturbances," International patent application 402582; European patent application 00967661.0-2411, January 2000; PCT WO 01/20804, March 2001; KPN N.V.

[BeP6] J. G. Beerends, A. P. Hekstra, "Method and arrangement for determining the quality of a signal using a two-step time averaging," International patent application 402607, EP 1250830, November 2000; PCT EP00/12535; KPN N.V.

[BeP7] J. G. Beerends, "Frequency dependent frequency compensation," International patent application 402736; PCT EP02/05556; European patent application 01203699.2, 2001; KPN N.V.

[BeP8] J. G. Beerends, "Method and system for measuring a system's transmission quality," International patent application 402808; PCT EP03/02058; European patent application 02075973.4-2218, April 2002; International patent publication WO 03/076889, 2003; KPN N.V. (Softscaling).

[BeP9] J. G. Beerends, "Method and system for speech quality prediction of an audio transmission system," International patent application 402894, European patent application EP03075949.2 2003, European patent EP04 714 792.1, KPN N.V. (Filter scale loop,).

[BeP10] J. G. Beerends, "Linear frequency distortion impact analyzer," European patent application EP04077601, November 2004, TNO Nederland N.V.

[BeP11] J. G. Beerends, B. Busz, J. M. van Vugt, O. A. Niamut and M. R. Bangma, "Method and system for speech quality prediction of the impact of time localized distortions of an audio transmission system," European patent application EP07006550.3, March 2007, Koninklijke KPN N.V. (time response degradation impact analyzer)

[BeP12] J. G. Beerends, J. M. van Vugt, R. A. van Buuren, "Speech quality and intelligibility measurement algorithm," premier depot, Oktober 2007, Koninklijke KPN N.V.

[BeP13] J. G. Beerends, J. M. van Vugt, "Method and system for determining a perceived quality of an audio system," International patent application 403457, European patent application 09010500.8, August 2009, Koninklijke KPN N.V. (Polqa Noise Impact Estimator).

[BeP14] J. G. Beerends, J. M. van Vugt, "Method and system for determining a perceived quality of an audio system," International patent application 403462, European patent application 09010501.6, August 2009, August 2009, Koninklijke KPN N.V. (Polqa Topology).

Section 1 (B1)
d. Extended Synopsis of the scientific proposal

Introduction

About 15% of the European population suffer from hearing impairments, mostly age-related (about 50% of the population aged 65 years and older have a hearing loss that needs to be aided). The demographic changes in combination with age-related hearing losses will result in an increasing number of hearing-impaired people in the European Union. Furthermore young people increasingly suffer from hearing loss as a result from listening to loud music. The Institute of Hearing Research (IHR) in the UK estimates that by 2015, about 90 million European adults will have a hearing loss. This makes people with hearing disabilities one of the largest disabled minorities.

Modern hearing aids aim at compensating for hearing losses by means of advanced digital signal processing, such as multi-band dynamic compression, single- and multi-channel noise reduction, de-reverberation, frequency compression and other advanced signal enhancement schemes. Although improvements of the performance of hearing aids have been achieved within the last decades, the benefit in terms of enhanced speech perception and sound quality are still deemed unsatisfying. Ratings of sound quality and acceptability are strong predictors of hearing aid use and/or satisfaction [1]. To date the most valid and reliable way to evaluate sound quality are formal subjective listening tests which are very costly, time consuming and are thus not suited for optimizing and checking hearing aid quality.

The goal of this project is to develop a perceptual hearing aid quality model with which the subjectively perceived quality can be predicted, not only allowing to check and optimize hearing aid quality but also to develop new hearing aids with better sound quality in shorter time at lower costs.

Objective quality assessment models

Up to date no objective quality assessment models with satisfactory performance and general applicability in the field of hearing aid sound quality evaluation could be developed. Encouraging results obtained with existing, perceptual quality models could only be achieved for some particular applications related to hearing aids, such as the evaluation of noise reduction schemes [2], [3]. In contrast, attempts to develop models with a broad scope of application did not achieve generally satisfactory results so far [4].

The current situation in the hearing aid industry resembles the situation in the telecommunication industries in the early nineties when a number of second generation mobile systems were introduced that used advanced speech coding systems of which the quality could not be measured objectively. At that time Beerends and Stemerdink developed the first world wide accepted standard for measuring speech quality, PSQM (Perceptual Speech Quality Measure, www.psqm.com, ITU-T Rec. P.861, 1996) [5], [6], [BeP1..4]. The follow up standard PESQ (Perceptual Evaluation of Speech Quality, www.pesq.org, ITU-T Rec. P.862, 2001) [10], [11], [12], [BeP6] was again for a major part developed by Beerends. In 2001 ITU-R standardized PEAQ (Perceptual Evaluation of Audio Quality, www.peaq.org, ITU-R Rec. BS.1387, 2001) which focuses on the quality of music codecs and which is for a large part based on the work developed by Beerends [7], [8], [9]. In the period 2006-2010 ITU-T again benchmarked several speech quality measurement systems and in 2011 PESQ is followed up by POLQA (Perceptual Objective Listening Quality Assessment, www.polqa.info, ITU-T Rec. P.863), which was again for a major part developed by Beerends [BeJ5], [BeJ8], [13], [BeP8..14].

The project goal: development of the objective quality assessment model

The goal of the project is to develop a perceptual hearing aid quality model for the objective, instrumental assessment of the sound quality of hearing aids that will not only allow for checking and optimizing hearing aid quality on the basis of the auditory profile of a subject but also to develop new hearing aids with better sound quality in shorter time at lower costs. It is even likely that the characteristics of this model can directly be translated into improvements in fitting rules and improvements of the hearing aid. To achieve this goal, two main approaches will be followed in the beginning of the project, possibly converging or combined at a later stage of the project. The first approach is based on the developments in the field of telecommunication which led to the ITU Recommendations P.861 (PSQM), BS.1384 (PEAQ), P.862 (PESQ) and P.863 (POLQA) and will be referred to as the *direct perceptual* approach. The second approach uses the basic ideas from advanced bio-physical and psycho-physical models as developed in the last decades [14]…[18] and will be referred to as the *basic* approach. This approach is pursued by the additional participating partner HörTech (dr. Rainer Huber), a leader in the development of basic speech and audio quality models [14], [15] that use advanced signal processing techniques reflecting the human auditory signal processing [16], [17], [18].

HörTech is one of Europe's top institutes in the field of hearing aid research and has its origins in a national contest of the German Federal Ministry of Education and Research in the field of biomedical engineering. Since it won this contest it has come to enjoy international appreciation and is now widely renowned for its efforts in applied research and development of new methods and knowledge regarding the supply and rehabilitation with hearing systems. Its expertise in the field of objective and subjective quality assessment, noise reduction technology, speech enhancement technology and hearing aid technology are essential in this project.

The combination of the know how from the telecommunication industry (TNO) where lately significant improvements have been made to predict sound quality in a wide range of listening conditions on the basis of direct modelling of the perceptual and cognitive processes with the advances made in the basic bio-physical and psycho-physical modelling (HörTech) provides the best possible starting point for the development of the quality model.

A possible spin off that may lead to ground braking improvements in the development of hearing aids is the discovery of certain types of signal processing that will enhance the perceived quality. It may allow for the development of an ideal hearing aid that can serve as a benchmark hearing aid**.**

How to get the subjective data for developing the quality model

A major problem in the development of a hearing aid quality assessment algorithm is the creation of subjective databases. Within normal subjective audio quality testing a large set of subjects is asked for their opinion and based on the average behaviour of the subjects a perceptual model is constructed using the approach of *figure 1*. The perceptual and cognitive models that are used in the objective measurement are based on the average normal human auditory system. The goal for a normal audio system under test is transparency and if the difference in the internal representation is zero the device under test behaves perfectly. By providing the subject with the ideal input signal the transparency ideal can be forced into the test. For signal enhancers the ideal signal can first be degraded and then enhanced forcing the measurement towards a transparency test. This approach allows assessing any audio system and has been very successful in predicting audio quality over an extreme wide range of audio systems. The latest ITU standard, POLQA [BeJ8], [13], also models the impact of play back level on quality, which plays a dominant role for hearing impaired subjects but was not taken into account in earlier ITU standards.

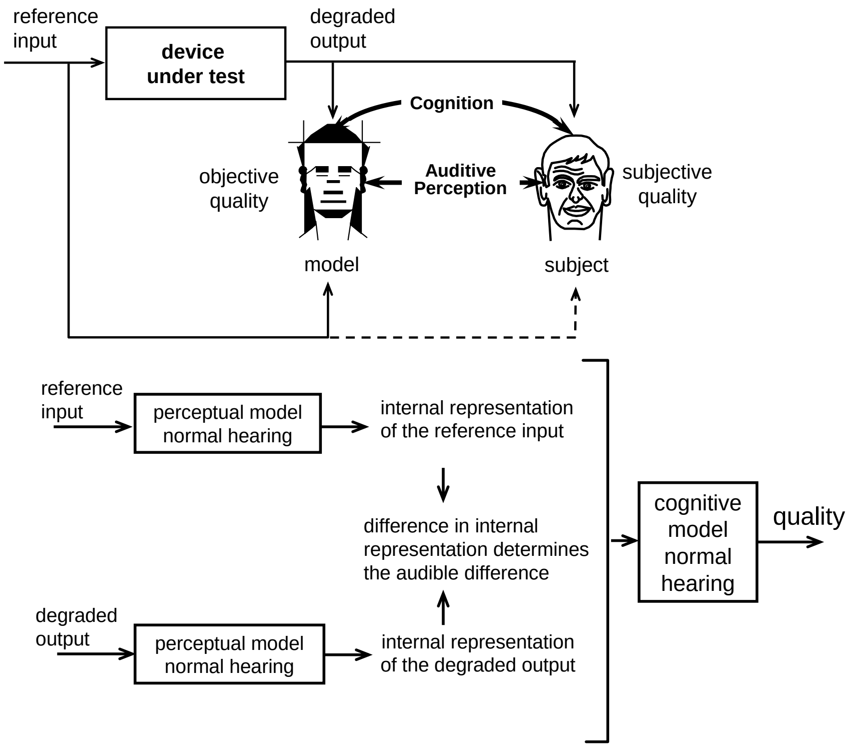

Figure 1. General approach in measuring audio quality for normal hearing subjects. The device under test is stimulated with a set of perceptual relevant test signals as reference input and both the subject and the model assess the quality of the signal based on the ideal of transparency. The perceptual model of the normal hearing subject is used to calculate the internal representation of reference and degraded signals. When the difference in the internal representation is zero the device under test is perfect.

For assessing the quality of a hearing aid one needs the individual characterization of the subject for which the hearing aid is designed. Averaging over large sets of subjects is thus not possible. A major portion of the research project is thus focussed on the construction of subjective databases which includes measures of the individual “auditory profile”, i.e., estimates of the individual suprathreshold distortion caused by the hearing loss. Averaging over large sets of subjects is not possible because the hearing aid that is being assessed is adapted to compensate for the specific loss of the hearing impaired subject (see *figure 2*).

The five work packages of development of the quality model

The **first** work package (wp1) of the project focuses on speech quality and starts with finding a set of subjects that have a similar hearing loss and no big deviations in their respective auditory profile. Only single ear evaluations will be used in this phase and the auditory profile will be determined by tone audiograms for the evaluated ears using standardized procedures [19]. With this set of subjects, normal hearing loss compensation strategies are evaluated using different methods of fitting starting with a widely accepted method (e.g. [20]). Using different play back level settings, equalization settings, compression schemes, noise suppression algorithms and types of distortions found in hearing aids a database is constructed containing the clean ideal reference signal and the signal processed by the hearing aid that is to be judged by the subject. For assessing noise suppression schemes different types of noise will be added to the speech signal, such as pink noise, babble noise, and car noise. The noise suppression schemes will then process the noisy speech signal and the output is judged by the subject. The expected outcome of wp1 are two different first models, one using the *direct perceptual* and one using the *basic* approach.

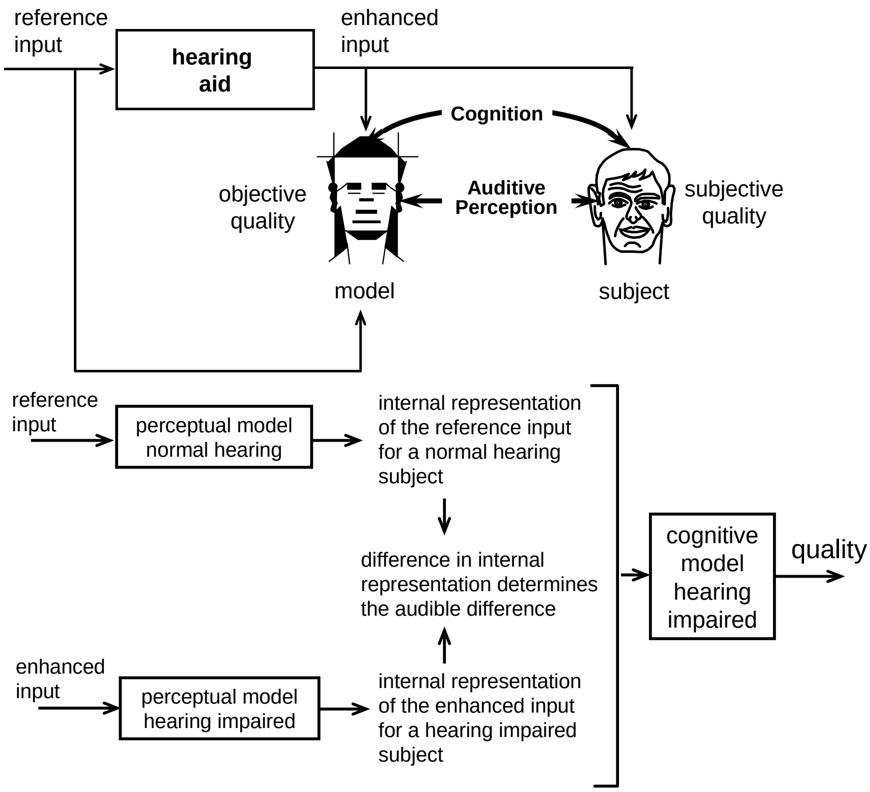

Figure 2. General approach in measuring the quality of a hearing aid. The hearing aid is stimulated with a set of perceptual relevant test signals and both the subject and the model assess the quality of the signal based on the ideal of transparency against having no hearing loss. The hearing aid is individually adapted to the subject that is tested. The perceptual model of the normal hearing subject is used to calculate the internal representation of reference, the perceptual model of the hearing impaired subject is used to calculate the internal representation of enhanced input. When the difference in the internal representation is zero the device under test is perfect.

The **second** work package of the project focuses on speech intelligibility using the same common auditory profile as used in the first work package. With this set of subjects the same processing types are applied as used in the first work package but then using higher levels of background noise. Using the ideas presented in [BeJ6], where the impact of distortions on intelligibility is quantified, an extension of POLQA and PEMO-Q will be developed for assessing speech intelligibility. The results of wp2 will be used to decide whether a full integration of the models is possible or that a double, context-dependent modelling is necessary.

The **third** work package of the project focuses on speech quality/intelligibility as perceived by subjects that are outside the common auditory profile. Two sets of tests are carried out, one using subjects having a auditory profile close to the group assessed in the first work package and one using subjects having a auditory profile completely different from the group assessed in the first work package, e.g. showing “dead regions” [21]. Hearing loss starts with damaged outer hair cells which form the active part of the inner ear and which introduce a rise in auditory threshold at the concerned frequency when damaged. The inner hair cells of the inner ear fulfil the role of passive transducers and when they are also damaged, a further rise in threshold up to a complete loss of signal will result. Signals in a narrow frequency band will then only become audible by stimulation of frequency bands outside the dead region. In the modelling not only the normal tone audiogram is used as an input but also other masking characterizations [22]. The expected outcome of wp3 is a model that can take into account the impact of dead regions on the perceived quality and possibly new rules that can be used to optimize hearing aids and their personalised fittings.

In the **fourth** work package it will be investigated if the model is able to predict the perceived quality of signals other than speech. Two categories will be investigated, music and background signals such as car noise, slamming doors, singing birds, wind blowing through trees, etc. It is known that hearing aid optimization is carried out in a context-dependent manner and especially the treatment of background signals and music is different from the treatment of speech. Speech processing should always have no degrading impact on intelligibility which can be assessed outside the context problem of speech quality, one either understands a word or not, no personal preference plays a role. The ideal speech processing should improve both intelligibility and quality, a goal that has not yet been realised with today’s processing algorithms. In the processing of background signals and music there is no single idealisation and the perceptual modelling is thus also different than the one used for speech assessment. The expected outcome of wp4 is a model that can take into account the impact of using music and background signals into the quality assessment.

In the **fifth** work package an extension will be developed that takes into account binaural processing. In both the subjective tests and the objective modelling the effect of listening with two ears will be investigated. All quality models up to now used a mono signal processing approach [5]...[18] and stereo subjective tests are simply assessed by running the model on both ears and taking the worst ear as the quality dominating ear. While being a researcher at KPN, Beerends experimented with a binaural streaming assessment which significantly improves the correlation between subjective obtained quality data and objective quality measurement [23]. It is expected that binaural streaming will also play a role in assessing hearing aid quality and that advanced binaural models [24] may further improve correlation between subjective and objective quality assessment. The expected outcome of wp5 is a model that can take into account the impact of binaural processing on the perceived quality and possibly new rules that can be used to optimize hearing aids and their personalised fittings taking into account binaural effects.

During the project results will be disseminated through publications in scientific journals that are focussed on hearing loss as well as technical journals that are focussed on audio signal processing. At the end of the project it is expected that we will not only have model for the objective, instrumental assessment of the sound quality of hearing aids, but also a set of processing rules that can directly be translated into improvements of the hearing aid and its fitting to individual auditory profiles. The results can be used by the hearing aid industry to develop new hearing aids with better sound quality in shorter time at lower costs. Furthermore it is expected that measurement equipment will come to the market using the model as developed with this ERC grant in the same manner as earlier developments of perceptual quality models with the telecommunication industry has resulted in measurement equipment based on PSQM (P.861), PESQ (P.862), POLQA (P.863) and PEAQ (BS.1387).

References

[1] L. L. N. Wong, L. Hickson and B. McPherson, “Hearing aid satisfaction: what does research from the past 20 years say?,” Trends Amplif, 7(4), pp. 117 -161 (2003).

[2] J. M. Kates and K. A. Arehart, ”speech quality metric based on a cochlear model,” J. Acoust. Soc. Am., vol. 125 (4), pp. 2723-2723 (2009 April).

[3] R. Huber, M. Schulte, M. Vormann, and J. Chalupper, “Objective measures of speech quality in hearing aids: Prediction of listening effort reduction by noise reduction algorithms,” Presented at

the 2nd Workshop on Speech in Noise: Intelligibility and Quality, Amsterdam, The Netherlands (2010).
Available: http://www.phon.ucl.ac.uk/events/quality2010/talks/RainerHuber.pdf

[4] L. Bramslow and M. Holmberg, "Validation of Objective Sound Quality Models for Hearing Aids, in Proceedings of the AES 38 th International Conference on Sound Quality, Pitea, Sweden (2010 June).

[5] J. G. Beerends and J. A. Stemerdink, "A Perceptual Speech Quality Measure based on a psychoacoustic sound representation," J. Audio Eng. Soc., vol. 42, pp. 115-123, (1994 March).

[6] ITU-T Rec. P.861, "Objective Quality Measurement of Telephoneband (300-3400 Hz) Speech Codecs," International Telecommunication Union, Geneva, Switzerland (1996 Aug.).

[7] J. G. Beerends and J. A. Stemerdink, "A Perceptual Audio Quality Measure based on a psychoacoustic sound representation," J. Audio Eng. Soc., vol. 40, pp. 963-978 (1992 Dec.).

[8] T. Thiede, W. C. Treurniet, R. Bitto, C. Schmidmer, T. Sporer, J. G. Beerends, C. Colomes, M. Keyhl, G. Stoll, K. Brandenburg, B. Feiten, "PEAQ - The ITU-Standard for objective measurement of perceived audio quality," J. Audio Eng. Soc., vol. 48, pp. 3-29 (2000 Jan./Feb.).

[9] ITU-R Rec. BS.1387, "Method for Objective Measurements of Perceived Audio Quality," International Telecommunication Union, Geneva, Switzerland (2001 Nov.).

[10] A. W. Rix, M. P. Hollier, A. P. Hekstra and J. G. Beerends, "PESQ, the new ITU standard for objective measurement of perceived speech quality, Part I - Time alignment," J. Audio Eng. Soc., vol. 50, pp. 755-764 (2002 Oct.).

[11][BeJ1] J. G. Beerends, A. P. Hekstra, A. W. Rix and M. P. Hollier, "PESQ, the new ITU standard for objective measurement of perceived speech quality, Part II - Perceptual model," J. Audio Eng. Soc., vol. 50, pp. 765-778 (2002 Oct.).

[12] ITU-T Rec. P.862, "Perceptual Evaluation Of Speech Quality (PESQ): An Objective Method for End-to-end Speech Quality Assessment of Narrow-band Telephone Networks and Speech Codecs," International Telecommunication Union, Geneva, Switzerland (2001 Feb.).

[13] J. Pomy, J. G. Beerends, C. Schmidmer, R. Ullman and J. Berger, "Stable Draft of New Recommendation P.863," ITU-T Study Group 12, White contribution COM 12-C141, September 2010 updated for the January 2011 meeting.

[14] M. Hansen and B. Kollmeier, "Objective modelling of speech quality with a psychoacoustically validated auditory model", J. Audio Eng. Soc. 48, pp. 395-409 (2000).

[15] R. Huber and B. Kollmeier, "PEMO-Q - A new Method for Objective Audio Quality Assessment using a Model of Auditory Perception." IEEE Transactions on Audio, Speech and Language processing 14(6), pp. 1902-1911 (2006).

[16] T. Dau, D. Püschel and A. Kohlrausch, "A quantitative model of the `effective' signal processing in the auditory system: I. Model structure,“ J. Acoust. Soc. Am. 99, pp. 3615-3622 (1996).

[17] T. Dau, B. Kollmeier and A. Kohlrausch, "Modeling auditory processing of amplitude modulation: I. Modulation Detection and masking with narrowband carriers,“ J. Acoust. Soc. Am. 102(5), pp. 2892-2905 (1997).

[18] R. P. Derleth, T. Dau and B. Kollmeier, "Modeling temporal and compressive properties of the normal and impaired auditory system," Hearing Research 159(1-2), pp. 132-149 (2001).

[19] ISO 8253, "Acoustics -Audiometric test methods," International Organization for Standardization (2010).

[20] D. Byrne and H. Dillon, "The National Acoustics Laboratories (NAL) new procedure for selecting gain and frequency response of a hearing aid", Ear and Hearing, 7(4), pp.257-265 (1986).

[21] B. C. J. Moore, "Dead regions in the cochlea: Diagnosis, perceptual consequences and implications for the fitting of hearing aids," Trends in Amplification 5(1), pp.1-34 (2001).

[22] B. C. J. Moore, B. R. Glasburg and M. A. Stone, "New version of the TEN test with calibrations in dB HL," Ear and Hearing 25(5), pp. 478-487 (2004).

[23] J. G. Beerends, "Device for determining the quality of an output signal to be generated by a signal processing circuit, and also method," International patent application 402247; European patent application 96201348.8-2215, EP 0901677, May 1996; International patent publication WO 97/44779, November 1997; KPN N.V. (audio binaural streaming).

[24] J. Breebaart, S. van de Par and A. Kohlrausch, "Binaural processing model based on contralateral inhibition, I. Model structure", J. Acoust. Soc. Am., vol. 110, pp. 1074-1088 (2001 Aug.).

[25] F. Rumsey, "Sound quality evaluation", J. Audio Eng. Soc., vol. 58, pp. 853-858 (2010 Oct.).