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REAL-LIFE HEARING PART 2: ASSESSMENT AND SOLUTIONS

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INTRODUCTION

In the first part of this article, "Real-Life Hearing – Part 1: The Theory Behind", a basic framework for explaining the entire hearing process was presented. The framework consists of four main elements as indicated graphically in Figure 1. These four elements of hearing constitute a continuous looped process where the elements interact with each other in a highly complex manner. The framework is valid whether or not a hearing loss is present and a hearing solution[1] is used – but both conditions will affect the elements and the interaction between them.

The starting point in the framework is the Acoustic Scene element. This is where the sounds from one or more sound sources are combined and reach the ears of a listener. In the next element, Auditory Processing, the sound is processed along the pathway going from the eardrum to the brain stem. The third element, Auditory Cognition, includes the cognitive processes that lead to sound perception – and speech understanding, in the important case where the sound is speech.

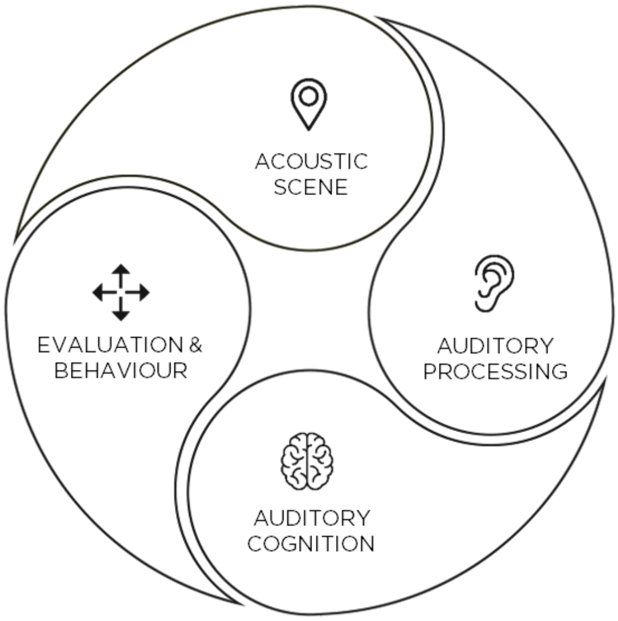

Figure 1. Framework showing the hearing process as a continuous looped flow involving four main elements.

In the fourth and final element, Evaluation & Behaviour, the listener evaluates and responds to the sound perception. In the case where listening is evaluated as being unsatisfactory, this may lead to a change in

[1] As in Part 1 of the article, the term "hearing solution" will in some cases be used as a synonym for "hearing aids", but it is mainly used to refer to the combined system of hearing aids and one or more connected devices, e.g. smartphones or Widex DEX devices.

behaviour – which will affect the experience of the Acoustic Scene, thereby closing the loop in the framework.

Traditionally, there has been a lot of focus on the hearing process that takes place at the right side of the framework, i.e. the Auditory Processing and its connection to Auditory Cognition. In Widex, we want to increase the focus on the left side of the framework – where the sound perception meets the individual listener's context, circumstances, intentions and emotions. This is where the traditional representation of hearing meets real life, and where the entire life of the listener is affected. This is what Widex refers to as Real-Life Hearing.

In this second part of the article, we will look into some of the research on Real-Life Hearing and address some of the possible methods available to assess it. We will also discuss some of the challenges involved in fitting hearing aids for Real-Life Hearing, and how these challenges have been addressed by Widex during the development of the Widex EVOKE™ hearing aid.

WHAT DO WE KNOW ABOUT REAL-LIFE HEARING?

The fact that hearing is happening out in real life and not in the lab, and that a lot of additional factors impact the listening process, is of course well known. But the high degree of individuality and complexity involved in Real-Life Hearing makes it quite complicated to study. It cannot be done by presenting pure tones via headphones to a test subject in the lab! Compared to the number of hearing studies performed in the lab, the number of research studies related to Real-Life Hearing is quite scarce. However, some interesting studies do exist. In the following, results from two of these studies – both carried out by ORCA Europe, Widex's research site in Stockholm, Sweden – will be presented.

The term "Auditory Ecology" has been suggested to describe the relationship between the acoustic environments experienced in everyday life and the perceptual demands of different people in these environments (Gatehouse et al., 1999). Thus, the term embraces the interaction between listener, listening demands and listening environments, which is central in Real-Life Hearing. ORCA Europe has completed a number of studies on topics relating to the auditory ecology of people with hearing loss. They have looked into the interaction between listener and listening environment, but they have also investigated the acoustic scenes encountered by people with hearing loss in their everyday life. Inspired by Noble (2008), they have suggested the term "Auditory Reality" to refer to "the variety of acoustic environments experienced by an individual" (Smeds & Wolters, 2017). In the context of the framework presented above, this corresponds to the acoustic scenes a listener is exposed to – shaped by the Auditory Processing and Auditory Cognition elements, but not including the Evaluation & Behaviour element.

In one study (Smeds et al., 2015), ORCA analysed data from a previous study by Wagener et al. (2008), where hearing-aid users had made recordings of typical situations in their everyday life. In the analysis, the recordings containing a target speech signal were picked out, and the signal-to-noise ratio (SNR) was estimated for each of these recordings. Furthermore, the speech recordings were classified into a number of categories (defined by the type of background noise). The purpose of this analysis was to get a qualified answer to a question, which previously had been only sparsely investigated: What are the typical SNRs experienced by people (with hearing loss) in their everyday life? Figure 2 shows the distribution of SNRs within each of nine different background-noise categories. A striking observation is that the vast majority of recordings had positive SNRs, and even in the noisiest categories, median SNRs were around +5 dB.

The observation that realistic SNRs are positive (and typically above 5 dB) is interesting, because it raises some questions about the ecological validity of the lab tests used in many hearing-aid assessments (i.e. how well the test performance predicts real-world performance). For example, it is not unusual to see hearing-aid users perform an adaptive speech-in-noise test at negative SNRs, when the target material is a closed set of words or sentences (e.g. the Danish matrix test, Dantale II, Wagener et al., 2003). This means that the hearing aids are tested at much lower SNRs than

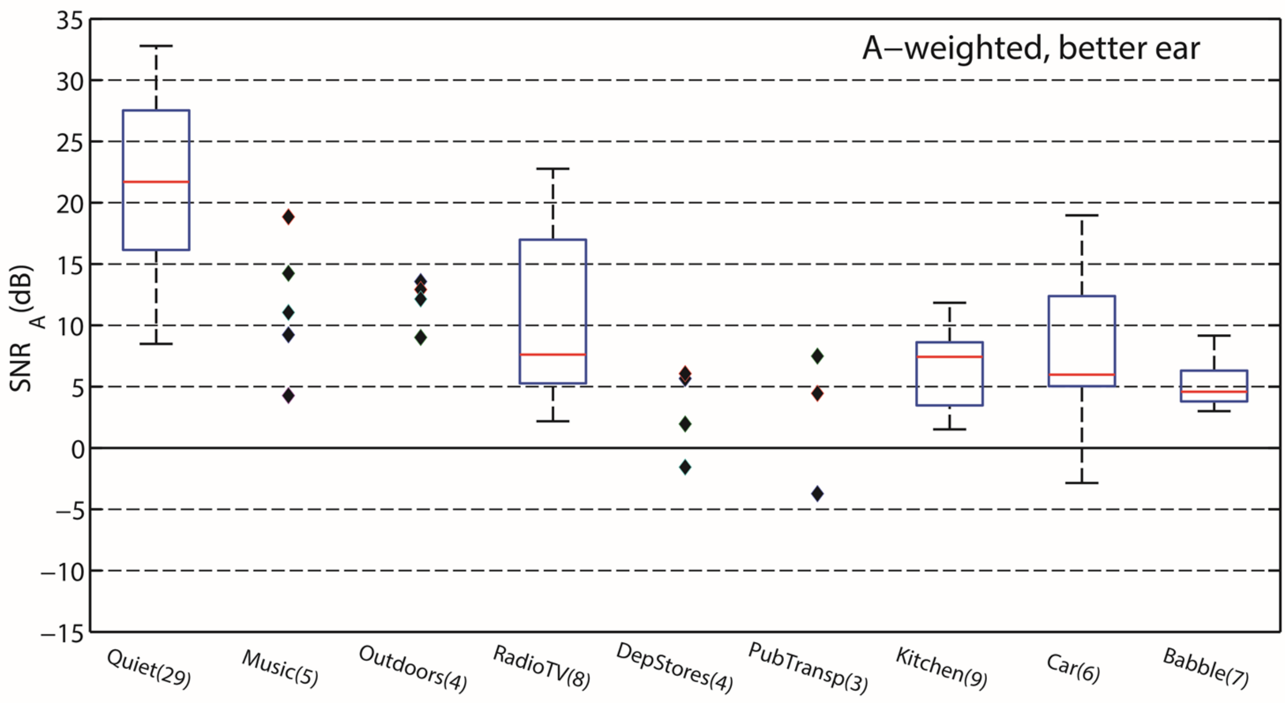

Figure 2. Box-and-whisker plot showing the minimum, maximum and quartile SNRs (calculated based on the A-weighted speech and noise levels at the ear with the better SNR) within each of nine different listening environments. The number of recordings within each environment is shown in parentheses. For categories with five or fewer observations, the single data points are plotted. From Smeds et al. (2015).

the SNRs, in which they will be used in real life. Furthermore, different participants may end up testing the hearing aids at very different SNRs. Since the functionality of a non-linear hearing aid will depend on the SNR, the results obtained in such a test may therefore be subject to an 'SNR confound effect' (Naylor, 2016), which in the worst case means that the results may be directly misleading regarding the real-life performance of the hearing aids. Thus, the findings about realistic SNRs may be used to develop new (lab) test methods with higher ecological validity.

In another study (Wolters et al., 2016), the ORCA researchers conducted a literature search to find previous studies investigating the acoustic environments and listening situations encountered during everyday life. They extracted the available data from the published articles and categorized it in different dimensions. The result was the Common Sound Scenarios (CoSS) framework that offers a systematic overview of the most common types of listening situation. The framework is shown schematically in Figure 3. It categorizes different listening situations according to three overall listening intentions ("speech communication", "focused listening" and "non-specific") and seven underlying listening tasks. For each task, two specific examples of sound scenarios are provided, together with an indication of the (typical) occurrence, importance and difficulty of each scenario.

The CoSS framework is intended to guide the selection of test scenarios used both during development of new signal-processing features and when testing a final complete hearing solution. While the framework obviously includes the important speech-communication situations, which are often in focus when assessing hearing-aid performance, it also includes more passive listening situations, which may be less demanding, but which occur frequently in most people's lives. Thus, the framework shows that Real-Life Hearing is not just about a few special situations – but rather about a broad range of situations with a high variety of listening intentions and tasks.

Intention	Speech communication						Focused listening				Non-specific			
Task	Two people		More than two people		Through device		Live sounds		Through media device		Monitoring surroundings		Passive listening	
	Two people having a conversation		Several people having a shared conversation		Two or more people having a shared conversation through a communication device		Focused listening to sound without being able to control the sound source		Focused listening to sound while being able to control the sound source		Conscious or unconscious screening of sound of relevance to current activity		Unconscious perception of environmental sounds, without relevance to current activity	
Scenario	#1	#2	#3	#4	#5	#6	#7	#8	#9	#10	#11	#12	#13	#14
Occurrence														
Importance														
Difficulty														
Scenario	Conversation at home	Conversation on metro	Meeting in an office	Car ride with family	Phone call at home	Mobile call in the street	Lecture	At a concert	Watching TV	Listening to car radio	Vacuum cleaning	City walk	Relaxing with a book	Relaxing on train

Figure 3. The Common Sound Scenarios (CoSS) framework. A colour indicator of occurrence, importance and difficulty of each scenario is provided, with darker shades representing higher values. From Wolters et al. (2016).

ASSESSMENT OF REAL-LIFE HEARING

Changing the focus from hearing to Real-Life Hearing will impact the assessment of hearing solutions. It suggests that some of the rather artificial lab tests (with limited ecological validity) should be replaced by real-life testing – or lab tests with a much higher degree of ecological validity. However, a major problem in this shift is that it may negatively affect the level of experimental control. That is, it may be harder to control what test participants are exposed to.

Unfortunately, there is often an inverse relationship between ecological validity and experimental control. Lab tests in well-defined surroundings (e.g. an anechoic chamber), using well-defined stimuli (e.g. narrow-band noise), and involving simple participant tasks (e.g. pressing a button when a sound is heard) have a very high level of experimental control, and it is possible to expose a group of test participants to exactly the same test procedure. However, the test has little resemblance to real life, end the ecological validity may be low. A traditional field trial, on the other hand, offers a very high level of ecological validity because it is performed in the participant's daily life, but the experimental control is low because each participant is exposed to varying and unknown stimuli, and different participants are not exposed to the same stimuli. Figure 4 shows how ecological validity and experimental control may be regarded as two dimensions in a 3D space. The third dimension, credibility, refers for example to the amount of statistical power (i.e. whether enough participants are included, given the reliability and sensitivity of the test), but it also covers other aspects like the choice of test site. Some sites may – due to their reputation – offer more credibility than others.

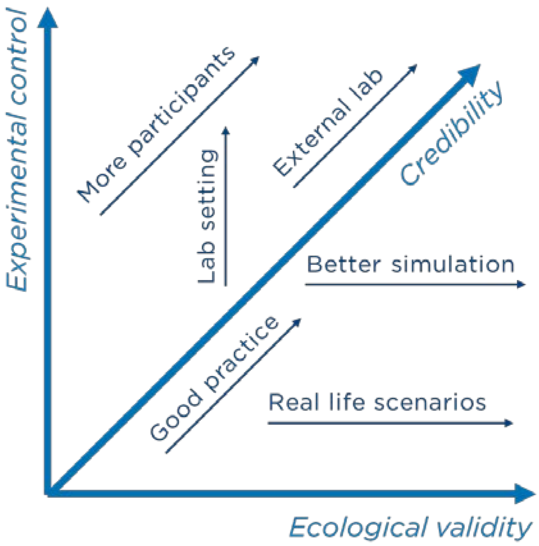

Figure 4. Test methods may be characterised by their ecological validity, experimental control, and credibility. The figure includes some examples of what can be done to improve in the different dimensions.

The ideal test will have a high score in all three dimensions. The figure includes examples of the actions which may be taken to improve in the different dimensions. For example, a better (lab) simulation of a sound scenario will increase the ecological validity; reducing the temporal variation in sound stimuli will increase the experimental control; and adding more test participants will improve the statistical power, and thereby the credibility, of a test.

Almost by definition, meaningful assessment of Real-Life Hearing requires a high level of ecological validity. The challenge is to find appropriate assessment methods that can offer this while still maintaining an appropriate level of experimental control and credibility. Some options are presented in the following paragraphs.

Ecological Momentary Assessment

Testing hearing solutions in real life is obviously not a new idea. Field trials have been (and still are) used frequently to assess the real-life performance of hearing aids, typically using some of the many standardised self-assessment tools (questionnaires), which have been developed over many decades. However, the traditional field trial suffers from several weaknesses. One of them is memory bias, which is introduced when a person at the end of a trial period (of perhaps several weeks) has to answer quite specific questions about the hearing experience during the period. The risk of not remembering a given listening situation – or remembering it incorrectly – is often quite considerable. Together with the general uncertainty (test-retest reliability) involved when responding to a questionnaire, this limits the overall reliability of the test approach.

The desire to overcome these weaknesses and the availability of new technology (smartphones), which offers new possibilities in the handling of questionnaires, have paved the way for a new assessment method, Ecological Momentary Assessment (EMA). The method originates from the field of clinical psychology (Shiffman et al., 2008), but the use of the method has spread to other fields, and in recent years it has gained interest within audiological research (see e.g. Wu et al., 2015).

The main idea of using EMA is to ask respondents about their perception of a (listening) situation while they are in the situation. This will minimize memory bias, maximize ecological validity, and allow investigation of factors influencing the user's evaluation in the given situation.

ORCA Europe has applied the EMA method in a study where the results clearly illustrate the potential of the method (Wolters & Townend, 2018). In the study, 10 participants with hearing loss were fitted with hearing aids including two programs, which the participant could switch between during a two-week trial period. The two settings included a reference setting (program A) and a test setting (program B), where gain was reduced in the mid-frequency range compared to setting A. The participants were equipped with a smartphone with an app. The app prompted the participants once every 1½ hours to compare the two settings (by switching between programs A and B) in the situation they were in and answer some questions asked by the app, e.g. which setting was preferred, and how the listening situation could be categorized (using categories based on the aforementioned CoSS framework).

The distribution of preference data among the four response options, and across all participants and all types of sound scenario, is shown in Figure 5. The plot shows that the reference setting (A) was given the highest share of preference indications.

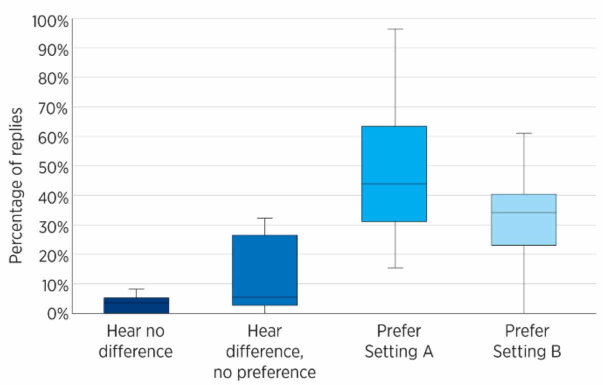

Figure 5. Distribution of preference scores across 10 participants (minimum, maximum and quartile shares of replies) and all types of sound scenario. From Wolters & Townend (2018).

A similar result pattern (i.e. A being somewhat better than B) could perhaps have been obtained in a more traditional field trial where the two settings were rated at the end of the trial. The real strength of the EMA

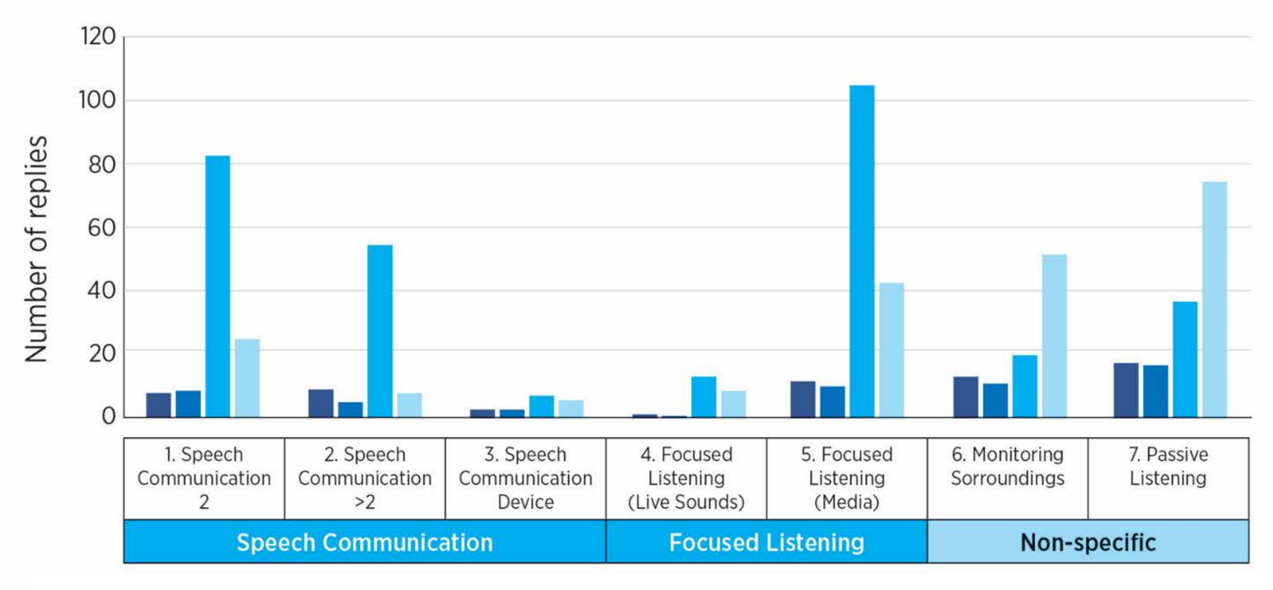

Figure 6. Distribution of preference scores within each of seven CoSS categories. From Wolters & Townend (2018).

method is its ability to provide more detailed results like the ones shown in Figure 6. In this plot, the preference data have been split into the seven CoSS categories (corresponding to different listening tasks) based on the participants' own classification. The plot reveals an interesting pattern, where setting A is preferred in situations with speech communication or focused listening, while setting B is preferred in non-specific situations where listening is passive or used to monitor surroundings. This pattern would not necessarily be revealed using a more traditional field-trial approach.

Another interesting aspect about the EMA approach is that it allows the individual participant to contribute many more data points than what a traditional field-trial approach normally allows. This allows for more detailed individual profiles of the participants to be constructed, and it enables investigations of how differences between individuals impact the results. This may also be exemplified using the results from the ORCA EMA study. Figure 7 includes individual spider webs that show how many listening-situation assessments were made in each of the seven CoSS categories by each of the 10 participants. Differences in the shapes are observed across the participants, indicating (not surprisingly) that the different participants had different acoustic realities, i.e. they experienced different types of acoustic scene during their everyday lives.

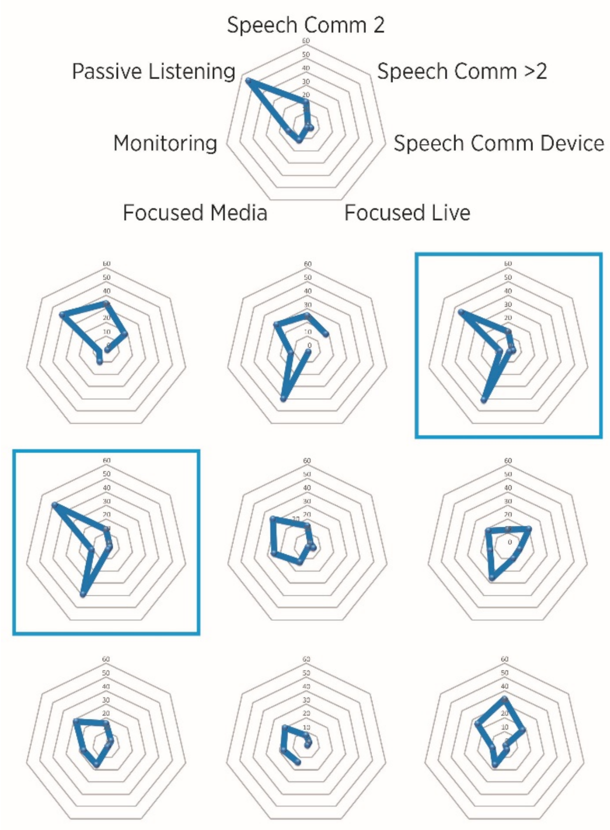

Figure 7. 'CoSS profiles' for 10 participants, indicating the number of assessments made within each of the seven CoSS categories (labelled in the upper plot). The framed profiles belong to the two participants with an overall preference for setting B. From Wolters & Townend (2018).

An interesting observation was made when the spider webs were held up against the overall preference (between settings A and B) expressed by the participants at the end of the field trial. The two participants who stated an overall preference for setting B (as highlighted in Figure 7) had a quite different 'CoSS profile' compared to the remaining participants who all preferred setting A. The two 'B profiles' were dominated by 'passive listening' and 'focused listening through a media device' (typically a TV), while active speech communication situations were almost absent in their everyday lives.

When the data in Figure 6 and Figure 7 are combined, it allows for a much more nuanced conclusion to be drawn than just that one setting (A) is better than the other (B). It provides detailed information about the actual situations in which one setting is better than the other, and how the auditory reality of the user impacts the preference. The ability to gather this type of knowledge is an important step towards designing hearing solutions which are better tailored to the individual user's Real-Life Hearing.

The EMA approach also allows data to be retrieved from the hearing solution in the situation where the assessment is made. This means that objective data about sound pressure level, the setting of various hearing-aid parameters, or data from sensors (in the hearing aid or in the smartphone) can be collected and compared to the data provided by the user. This will further contribute to an improved understanding of individual users' real-life-hearing patterns, and this knowledge will enable the development of new hearing solutions that better address specific individual needs. Until now, the EMA method has primarily been used in research contexts, but the possibilities offered by the method could make it very useful in clinical contexts as well.

Use of EEG

Electroencephalography (EEG) has for many decades been used to measure brain activity. In recent years, it has also been a popular tool in auditory neuroscience where it has shed light on some of the cognitive processes which take place in the Auditory Cognition element. For example, research has suggested that enhanced alpha power (EEG oscillations around 8-12 Hz) reflects the listening effort that is spent during the cognitive part of the listening process (e.g. Obleser et al., 2012). While it is still somewhat unclear which cognitive processes the alpha-power measurements reflect (Miles et al., 2017), the possibility of using EEG to objectively measure listening effort is quite intriguing.

The EEG measurements performed in auditory research are normally conducted by placing multiple electrodes on the scalp using a cap like the one shown in the picture on the left in Figure 8. This set-up is not very practical and only applicable in lab tests with rather limited ecological validity. The fact that the ear canal is quite close to the brain means that it provides possibilities for capturing EEG signals that are appropriate for analysis. This has led to the idea of placing EEG electrodes in an earmould and in that way obtaining a much more practical and ecologically valid measurement set-up (see picture on the right in Figure 8. This in-ear EEG set-up could be used to collect data in the wearer's real life, e.g. by making it part of a hearing solution.

Figure 8. Left: Traditional EEG measurement set-up using a cap with electrodes. Right: Earmould equipped with electrodes used for in-ear EEG. Pictures provided by UNEEG medical.

Various applications of an in-ear EEG system can be imagined. For example, if a valid measure of real-time listening effort could be extracted, it could be used to control the signal processing in a hearing aid – offering different solutions depending on whether a given situation is effortful or not. Another possible application could be to steer a beamformer (or other signal-processing features) based on EEG measurements of the user's attention in the given situation.

While it is possible to formulate a lot of visions for the use of in-ear EEG, it should also be acknowledged that a lot of research and development remains to be done before an EEG system will be ready for implementation in a commercially available hearing solution. However, this R&D work is going on right now with UNEGG medical, a company in the Widex group, being an active player in the field.

In-ear EEG is only one of a number of methods using various sensors – built into a hearing aid or positioned in a smartphone – which have been suggested as part of a hearing solution. Data from sensors may be used to tap into the factors that determine the user's evaluation of a given listening situation and thereby guide changes in the signal processing, which may improve the user's Real-Life Hearing. However, the sensor data may also be used for other (non-auditory) purposes, e.g. various types of health monitoring. As for in-ear EEG, the number of possible applications for sensors integrated into hearing solutions is virtually unlimited.

FITTING HEARING AIDS FOR REAL-LIFE HEARING

Real-life hearing reflects the basic fact that people are different, have different (and varied) auditory realities, and have different auditory needs. While this is quite obvious, it is not well reflected in the traditional way of fitting a hearing aid. This fitting approach is to a large degree based on the information available in the audiogram and a 'one-size-fits-all' approach. Two people of the same gender with identical audiograms and years of hearing-aid experience basically get the same hearing-aid fitting even though they may have very different auditory realities and needs.

In practice, this is not quite true. A skilled hearing care professional (HCP) will attempt to uncover the individual needs and use the fitting tools available to tailor the hearing solution to accommodate the user's needs in the best possible way. However, for the fitting process to succeed, it requires 1) that the user is able to express the needs; 2) that the HCP is able to make the right interpretation of the user's explanation; and 3) that the HCP is able to set up the hearing solution in a way that meets the needs. This process happens all the time when HCPs fit hearing aids, but it involves a number of possible 'translation issues'. Explaining how a sound is perceived is typically much harder than explaining a visual impression – where the use of shapes, colours, materials, and dimensions allows a fairly precise verbal description of a given object. It is sometimes very difficult, or even impossible, for an HCP to make the correct interpretation of the user's statements, which is obviously needed in order to determine and provide the optimal hearing solution.

Another issue when fitting hearing aids for Real-Life Hearing is that neither the user nor the user's auditory reality is static. The user will experience a multitude of different acoustic scenes where listening intentions are quite different. Even within the same acoustic scene, the listening intention may shift from one moment to the next.

While a modern hearing aid is designed to adapt its signal processing to provide optimal user satisfaction in a variety of different acoustic scenes, it should be acknowledged that it does this by applying some general assumptions about the listening intentions in those acoustic scenes. In many cases, the assumption will match the user's actual listening intention fairly well – but in some cases, it will not. In these cases where the hearing solution does not meet the individual user's needs, a possible solution is to empower the user to adjust the hearing solution to better support the listening intention and thereby improve the total listening experience. This option could in its simplest form be access to a volume control, which allows the loudness to be changed. More advanced options could be access to multiple programs or to an equalizer, controlled by an app, which allows a spectral shaping of the sound. However, all these options require that the user has a very clear idea about what it takes (in terms of adjustments) to reach the desired performance.

It is not difficult to imagine a listening situation that is judged to be unsatisfactory by the user of a hearing solution, and where the user is unable to determine an adjustment of the hearing solution (or another behavioural action) that provides an improvement (cf. the Evaluation & Behaviour element in Figure 1). How to empower the user in this type of situation is a challenge that has inspired the development of the SoundSense Learn option in Widex EVOKE™. This option allows the user to adjust some of the parameters in the hearing aid, leading to an improved listening experience, without being able to express the problem and without knowing which parameters to adjust and how they should be adjusted.

SoundSense Learn is based on the use of a machine-learning algorithm utilizing advanced Bayesian statistical modelling (Nielsen et al., 2015; Townend et al., 2018). The algorithm learns from responses made by the user and provides an estimate of a preference function, which maps the level of user satisfaction as a function of the hearing-aid-parameter setting. When the preference function is known, the maximum of the function determines the parameter setting that optimizes the user satisfaction in the specific acoustic scene. The only thing the user needs to do is to listen to two different settings of the hearing-aid parameters – A and B, suggested by the machine-learning algorithm – and indicate the preferred setting using a simple and intuitive interface in the EVOKE™ app. This starts an iterative process where the algorithm will update the estimated preference function after each comparison and suggest two new settings for the user to compare. Repeating this process will bring the hearing-aid setting closer and closer to the optimal setting. Noticeable improvements may be obtained after just a few iterations, and the optimal setting is typically reached within 20 comparisons.

A recent study has shown that individual settings of Widex EVOKE™ based on completion of the SoundSense Learn procedure provide significant improvements in perceived sound quality and comfort compared to the Universal setting (Townend & Ramsgaard, 2018). Figure 9 shows mean ratings of sound quality and comfort, averaged across 19 participants and three sound samples. The setting based on the use of SoundSense Learn was compared to the Universal setting with and without activation of the Fluid Sound Analyzer. It is noticeable that activation of the Fluid Sound Analyzer in itself provides a substantial improvement, showing the benefit of the automatic sound classification. However, the use of SoundSense Learn results in an additional and statistically significant improvement in the mean ratings of both sound quality and comfort.

Another important finding in the study is that there were no systematic differences across participants between the starting point (the prescribed setting) and the adjusted setting determined by the SoundSense Learn procedure. Thus, different participants required different adjustments of the hearing aids, and, therefore, these improvements could not be obtained by implementing a general change in the prescribed setting. This finding is a clear indication that hearing-aid users do indeed have different needs, and, accordingly, need different solutions.

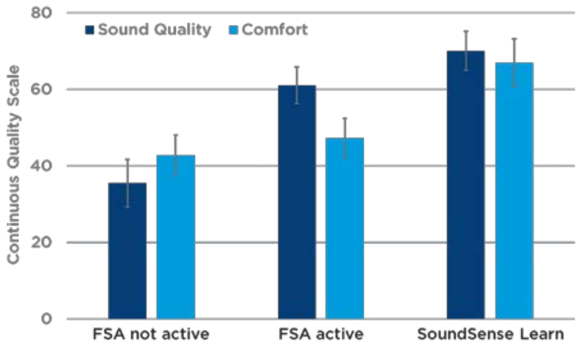

Figure 9. Mean ratings (across 19 participants and three sound samples) of sound quality and comfort for three different hearing aid settings: the Universal setting with and without activation of the Fluid Sound Analyzer (FSA) and the setting based on the use of SoundSense Learn. Error bars indicate 95% confidence intervals. From Townend & Ramsgaard (2018).

Widex EVOKE™ also includes the SoundSense Adapt option, which utilizes the user's (conscious) adjustments of the preference control to determine a gradual change of the basic parameter setting of the hearing aid. This will bring the setting closer and closer to the optimal setting for each of the 11 sound classes. This means that if a user adjusts the preference control in a systematic way each time he or she enters a given acoustic scene, the need for adjustment will gradually decrease over time. Eventually, adjustments will not be needed anymore because the optimal setting has been reached. That is, the hearing aid has adapted its processing characteristics to the user's Real-Life Hearing needs.

SUMMARY

The first part of the article described a framework in which the entire hearing process is described as a continuous loop consisting of four main interconnected elements. The framework is built upon a traditional description of the hearing process, where the acoustic sound stimuli are translated into sound perception, but this is extended and bound together by taking the real-life context, circumstances, intentions and emotions of the listener into account in the description of the full process. This is what Widex refers to as Real-Life Hearing.

In this second part of the article, some of the evidence behind the concept of Real-Life Hearing, gathered by ORCA Europe, is presented. Their studies on people with hearing loss have shown a variation in auditory reality – both within and between people – that indicates the need for new hearing solutions that better address individual needs.

Furthermore, assessment of Real-Life Hearing requires new assessment methods, and results from an ORCA study using an Ecological Momentary Assessment approach were presented to demonstrate how individual auditory-reality patterns may be used as an indicator for preference between different hearing-aid parameter settings.

The SoundSense Learn and SoundSense Adapt features available in Widex EVOKE™ are concrete examples of sophisticated yet user-friendly options that are made available to empower users of Widex hearing solutions to address – and improve – their Real-Life Hearing.

Widex has acknowledged and begun to integrate the importance of real-life evaluation of hearing and hearing solutions and the users' perception of the sound into the products and services we deliver. Real-Life Hearing is about extending the hearing journey further than before, beyond not just the ear, the brain and the clinic but also out into the real world. Widex wants to explore hearing and the performance of hearing solutions where it actually happens. We will use this knowledge to develop products that allow users to interact with their hearing aids in the moment in new and powerful ways. By doing this, Widex hopes to make a real and meaningful difference to the users of our hearing solutions. A difference today and far into the future.

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