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REAL-LIFE HEARING PART 1: THE THEORY BEHIND

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INTRODUCTION

The importance of the sense of hearing to everyday life is well known, and so are the consequences when this sense is impaired. Research has provided a vast amount of knowledge about the function of both the healthy and the impaired ear, and the various – individual as well as societal – negative consequences of hearing loss (e.g., Moore, 1996; Dalton et al., 2003; Archbold et al., 2014; WHO, 2017).

Audiological and auditory research has for many years focused on the function of the 'lower-level' parts of the human processing of sounds, i.e. the processing in the auditory periphery (the external, middle, and inner ear). In recent years, in parallel with general advances in neuroscience, there has been an increasingly strong research focus on the 'higher-level' processing of sound, i.e. the processing in the auditory nerve and in the brain. This research has shed light on how sound is processed in the brain, and how human perception and cognition of sound are obtained.

In particular, the knowledge about speech perception has increased, and models are now available to explain the cognitive mechanisms involved in speech understanding. These models have been useful when designing hearing-aid signal processing aiming at optimizing a hearing-aid user's ability to understand speech.

Despite the increased knowledge about audiology and cognition, and the corresponding major improvements in hearing technology over the last decades, there are still needs and demands of people with hearing loss that are not addressed optimally by current hearing solutions[1] when used in real life. For example, recent hearing-aid-user surveys like the MarkeTrak IX survey (Abrams & Kihm, 2015) show that the 'classic' problem of not being able to follow a conversation in a noisy background is still a substantial issue for many hearing-aid users.

Widex wants to address this gap between what hearing solutions based on traditional audiological knowledge

[1] The term "hearing solution" is used frequently in this article. In some cases, it will be used as a synonym for "hearing aids." However, it is mainly used to indicate that other devices may be connected to – and used together with – the hearing aids. This could be a smartphone connected to the hearing aids, or it could be a remote control or another type of assistive device (e.g. the Widex DEX devices). Thus, hearing solution refers to the combined pool of devices.

can provide and what the individual user of a hearing solution needs out in real life. We want to provide hearing solutions that address the fact that, in real-life listening situations, the context, circumstances, intentions and emotions of the user are not constant factors. These factors affect the listening experience. They vary both between and within users, and they have typically not been addressed in the studies of the auditory function that have provided a lot of the knowledge, on which current hearing solutions are based. Thus, Widex wants to address the obvious fact that hearing takes place out in the real life where a lot of aspects not accounted for in lab studies come into play.

In this article, a basic framework attempting to embrace all elements of the hearing process is presented. A special focus is made on the part of the framework where the traditional (lab-based) representation of the hearing process meets the real life of a listener. This part ties together the entire hearing process and allows the process to be regarded as a continuous looped flow. The intersection between sound perception and individual context, circumstances, intentions and emotions – where hearing meets real life – is where the entire life of the listener is affected, and this is what Widex refers to as Real-Life Hearing!

THE ELEMENTS OF HEARING

Real-Life Hearing builds on all the existing knowledge about the hearing process, which has been gathered during decades of audiological research. To understand Real-Life Hearing, it is necessary to have an overview of all the elements involved in the hearing process.

To facilitate the understanding of the hearing process – and eventually Real-Life-Hearing – Widex has created an audiological framework in which the entire process of hearing is split into four separate but highly interconnected main elements. The framework is illustrated in Figure 1, which indicates how the elements are tied together in what could be regarded as a looped (clock-wise) continuous process – with a highly complex interaction between the elements.

In principle, the basic framework is valid whether or not a hearing loss is present and whether or not a hearing solution is used. However, when a hearing loss is present, and a hearing solution is used, it will impact both the individual elements and the interaction between them.

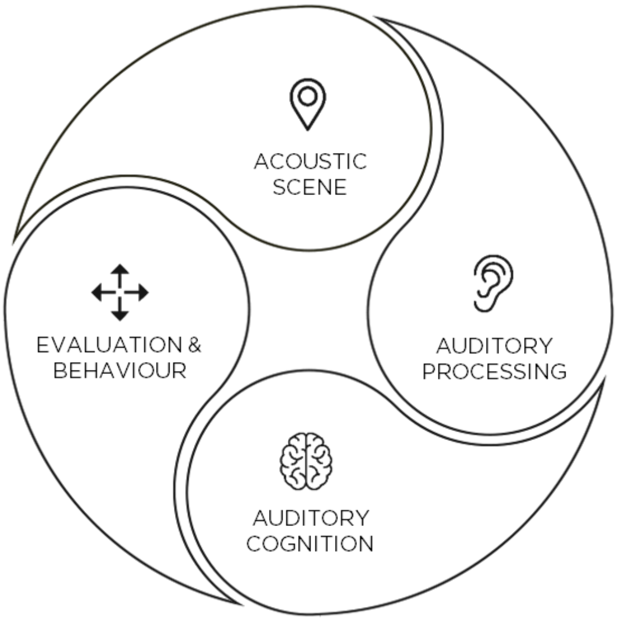

Figure 1. Framework showing the hearing process as a continuous looped flow involving four main elements.

In this chapter, each of the elements will be described separately. It will be explained how they interact and are impacted by a hearing loss and by the use of a hearing solution. It will become evident how Real-Life Hearing becomes the result of taking a full loop in the framework shown in Figure 1.

Acoustic Scene

The hearing process starts when sound reaches a person – who then becomes a listener. The acoustic part of the listening situation may be referred to as an Acoustic Scene. The scene is created by a number of sound sources in given positions around the listener (and perhaps including the listener, e.g. when speaking). Thus, in the Acoustic Scene element there is a focus on the physical stimuli that reach the listener.

Figure 2 shows a basic model of the Acoustic Scene. The transmission of sound from each sound source to the position of the listener is characterized by an acoustic transfer function, which is determined by the location of the source and the listener, and by the

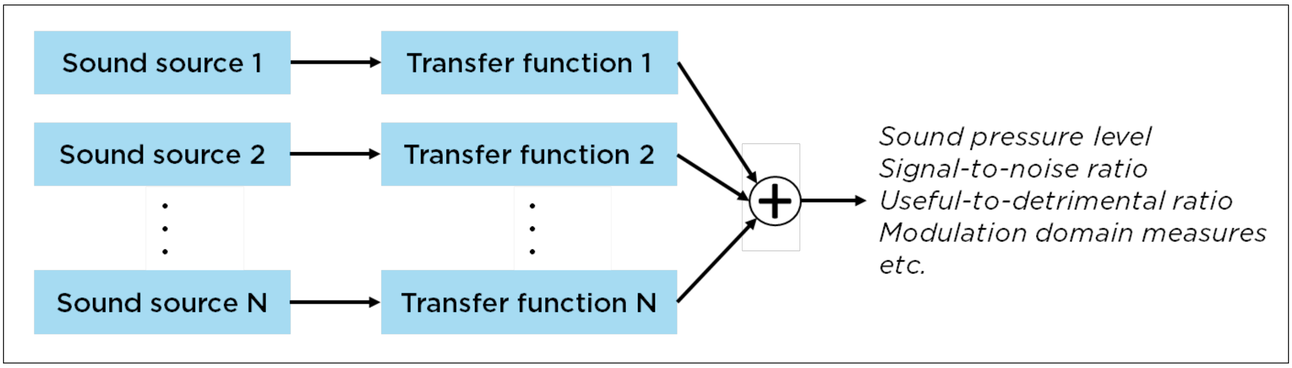

Figure 2. Model description of the Acoustic Scene. The sounds from each of N separate sound sources are shaped by corresponding transfer functions. As indicated on the output side, the combined sound may be characterized in different ways.

acoustic properties of the surroundings (e.g., the surfaces of a room). In a free (non-reverberant) sound field, the transfer function is known as the head-related transfer function (HRTF). When there is an acoustic effect of a room involved, the transfer function may be characterized by the binaural room impulse response (BRIR). The contributions from the different sources, which typically consist of both direct and reflected sound, are combined at the position of a listener.

The sound signal reaching the listener may be characterized by a wide variety of acoustic measures, with some of the more basic ones being the sound pressure level (SPL) and the signal-to-noise ratio (SNR: relevant in the case where one sound source can be considered 'signal' and the others can be considered 'noise'). These and other relevant characteristics may be derived from analysis of the acoustic signal captured by a hearing-aid microphone. Many hearing solutions use these types of measures to classify the acoustic scene in several pre-defined generic listening situations and provide different signal processing strategies accordingly. The Fluid Sound Analyzer, which is implemented in Widex EVOKE™, operates with 11 different sound classes, each designed to optimize listening performance in a given type of acoustic scene.

Acoustic Coupling

The next element shown in Figure 1, Auditory Processing, comes into play when sound reaches the eardrum of the listener. However, the characteristics of the sound reaching the eardrum will depend on whether a hearing solution is used or not. Therefore, it makes sense to talk about the acoustic coupling between Acoustic Scene and Auditory Processing as a separate (fifth) element in the framework.

In the unaided case, without use of a hearing solution, the acoustic coupling between Acoustic Scene and Auditory Processing is basically the open ear channel, which adds a spectral shaping to the sound due to the ear canal resonance.

In the aided case where a hearing solution is used, the acoustic coupling becomes more complicated. This is shown in Figure 3, which illustrates how sound processed by a hearing aid, sound transmitted through the vent of the hearing aid, and sound transmitted through the body of the hearing-aid user (most pronounced when the user is speaking) are combined – and interfere with each other – in the residual volume between ear piece and eardrum. The feedback path created by the vent, which is also indicated in the figure, contributes further to a highly complex system. Detailed knowledge about the different paths is needed in order to estimate the outcome, i.e. the sound pressure at the eardrum.

The ability to control the sound pressure at the eardrum is obviously important when fitting a hearing aid. Fitting precision, i.e. the ability to provide the prescribed output and gain in the individual ear, has always been a focus point for Widex, and this has led to innovations like the Sensogram (Kuk et al., 2003), the SoundTracker (Oeding & Valente, 2013), and the Assessment of In-situ Acoustics (AISA; Kuk & Nordahn, 2006), which contribute to the accurate 'match to target' performance offered by current Widex hearing aids (Schmidt et al., 2017).

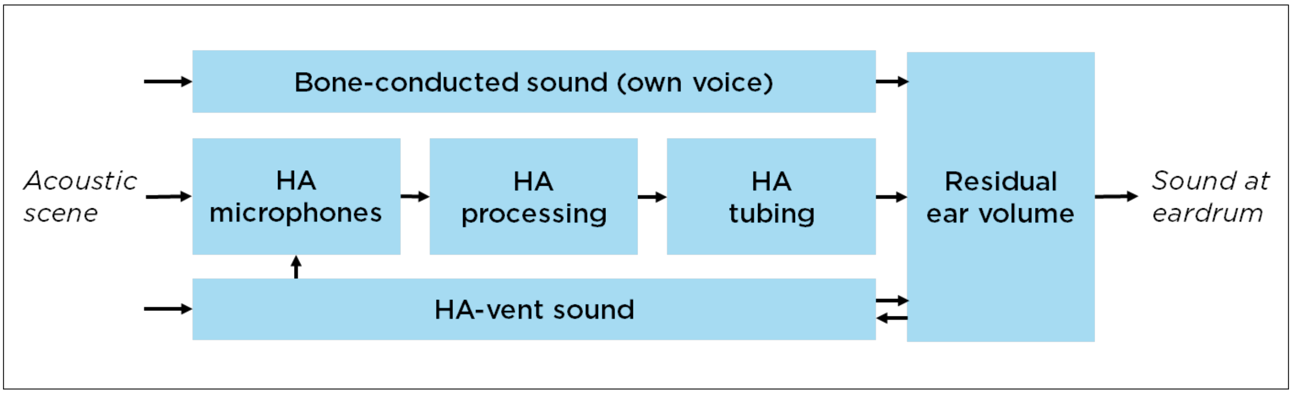

Figure 3. Basic model of the acoustic coupling between Acoustic Scene and Auditory Processing when a hearing aid (HA) is used.

Auditory Processing
The Auditory Processing element includes the signal-transmission path from the eardrum to the auditory cortex, in which the acoustic signal reaching the ear is transformed to an electrical signal in the brain. As shown schematically in Figure 4, it involves the stages of the auditory pathway where the most common types of hearing loss have their physiological origin. An in-depth understanding of the functionality of the different stages along the path, the types and nature of hearing loss which may occur and the perceptual consequences of these different types of hearing loss is obviously a fundamental requirement when developing solutions to compensate for a hearing loss.

Sensorineural hearing loss caused primarily by loss of outer hair cells in the cochlear is of special interest when dealing with hearing aids because it is the most common type of hearing loss treated by hearing aids. The loss of outer hair cells causes a loss of the nonlinearity in the 'cochlear amplifier', which gives rise to the well-known recruitment phenomenon (abnormal growth of loudness) that characterizes a sensorineural hearing loss, and which is the reason for the prescription of non-linear gain (wide dynamic range compression) used in all modern hearing aids.

The auditory-processing path is fairly well investigated, and a detailed description can be found in various textbooks on the auditory system (e.g. Pickles, 2013). However, there are still parts of the Auditory Processing element that need to be investigated further. An example is the entire topic of 'hidden hearing loss' (HHL), also known as 'cochlear synaptopathy' (Kujawa & Liberman, 2009). HHL refers to the case where a person with a normal pure-tone audiogram has a reduced ability to understand speech in noise. It has been suggested that exposure to loud noise under certain circumstances may lead to damage of the synaptic connections between the inner hair cells in the cochlea and the afferent nerve fibres in the auditory nerve, while leaving the hair cells intact. The theory is that the reduced number of functioning synapses is sufficient to transmit a simple signal like a pure tone (when measuring the audiogram), but insufficient to transmit more complex signals like speech in a background of noise. However, the HHL theory has not been confirmed and is currently being debated. The

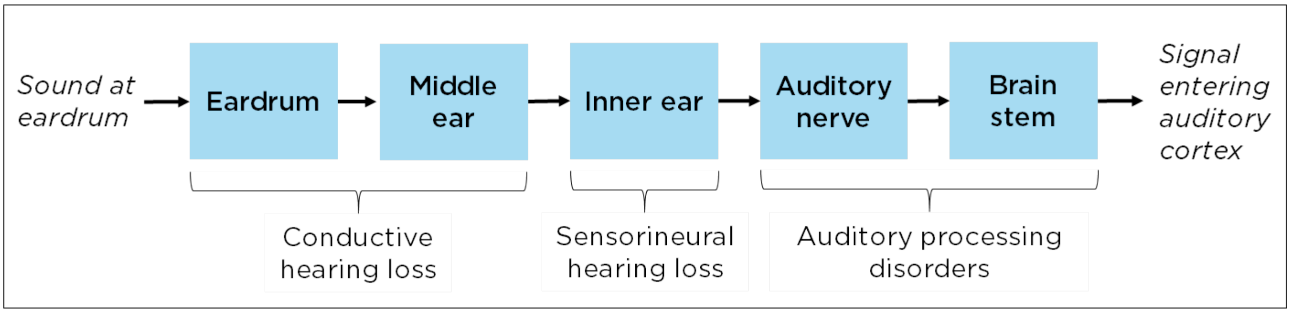

Figure 4. Basic model of the Auditory Processing element.

HHL mechanisms in humans are still not well understood, and a method to detect HHL is still lacking.

Auditory Cognition
"You hear with your ears, but listen with your brain". This mantra (or variations of it) has been used for years to indicate the evident fact that it is the processing that takes place in the brain, that determines how the sound signal coming through the Auditory Processing element is perceived by a listener. In particular, when the sound signal is speech, the function of the Auditory Cognition element is central in the process of deriving meaning from the speech signal, i.e. to make the listener understand what is being said.

The Auditory Cognition element is highly complex. It is mediated by the different patterns of neural activities across various subcortical and cortical centres of the brain, and many aspects of it are still not well understood. However, especially within the last few decades, auditory neuroscience has made a lot of progress and various conceptual models are now available to explain the processes involved in speech understanding.

To provide an explanation of Auditory Cognition, we have combined some widely accepted models into the model shown in Figure 5. The main inspiration comes from the Ease of Language Understanding model (ELU, Rönnberg et al., 2008; Rönnberg et al., 2013), augmented by Edwards (2016) who included Auditory Scene Analysis (Bregman, 1990) in the model, and further inspiration has been found in work by Pichora-Fuller et al. (2016) and Shinn-Cunningham (2008).

The input to the Auditory Cognition element is the signal arriving at the auditory cortex. In the first block, named Auditory Object Formation, auditory scene analysis is performed where the incoming sound is divided into a number of separate streams. Ideally, these streams will correspond to the sound sources present in the acoustic scene, but if the output signal from the Auditory Processing is degraded, e.g. due to a hearing loss, the cues needed to perform the object formation may be degraded as well, and the result will be that the streams are not segregated correctly. This will impact the following blocks in the element.

The ability to perform the stream segregation is important for the next block (process) in the model, Auditory Object Selection, where the listener steer her attention towards the stream of interest, e.g. the speech signal coming from a particular talker surrounded by other talkers. When the selection process is disturbed by imperfect object formation, the selection task becomes more difficult, and a higher share of the listener's working memory needs to be activated to complete the task. This allocation of cognitive energy (by use of the working memory) to a given task is often referred to as effort – and since this task involves listening, it is called listening effort.

Listening effort also comes into play in the next stage of the model, which explicitly deals with speech

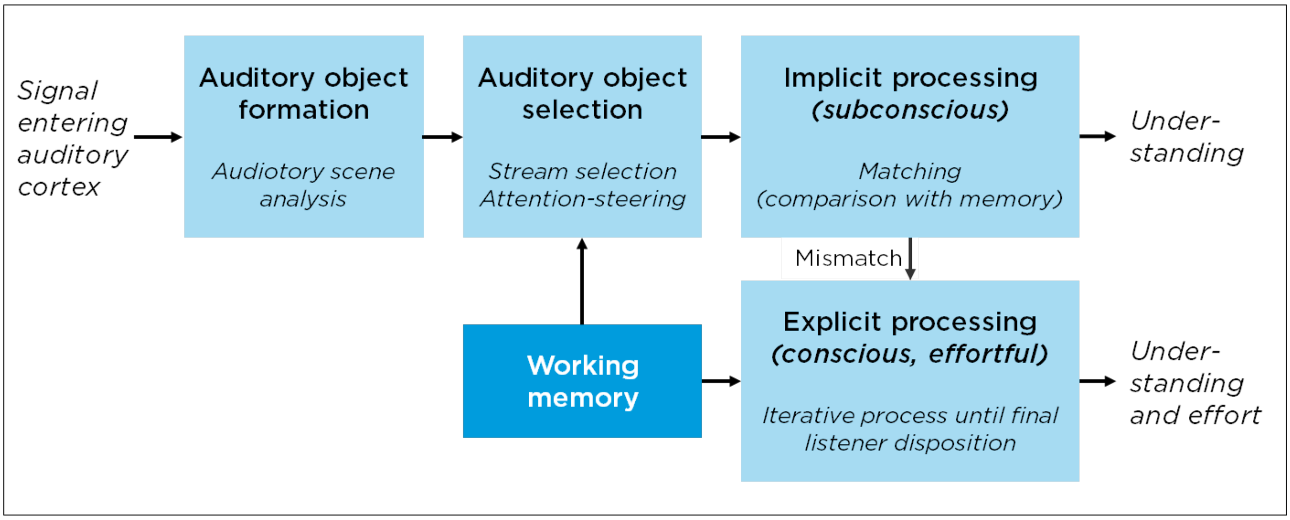

Figure 5. Basic model of the Auditory Cognition element, focusing on speech perception.

understanding. This stage uses the ELU model to explain how speech understanding occurs. The ELU model suggests that the phonological information in the input signal (i.e. the speech stream which the listener attends to) is compared with the phonological representations stored in the long-term memory. When an easy match is obtained – e.g. when listening to clear speech in quiet surroundings – speech understanding happens subconsciously, referred to as implicit processing. However, when a mismatch occurs, a conscious process, referred to as explicit processing, is initiated where the listener uses the working-memory capacity to obtain the understanding, e.g. by using the context to guess what was being said.

There may be different reasons for a mismatch. One could of course be that the listener has a limited vocabulary in the language being spoken. Another reason could be that the lexical access used during the matching process is slow due to cognitive decline. But it could also be caused by a hearing loss that reduces the audibility of the speech, or by various artefacts created by a hearing aid's sound processing. Thus, keeping artefacts such as distortions or acoustic feedback at a low level is not only a matter of optimizing the perceived sound quality. It is also a matter of reducing the cognitive load during the processing of speech.

Activation of the explicit processing may allow the listener to understand speech. However, it comes at the cost of having to spend working-memory capacity, and thereby listening effort, to solve the task. Since working memory is a limited resource, the task may become so difficult that the listener runs out of cognitive resources and therefore has to give up. The amount of available cognitive resources, and in particular the amount of working memory, varies across people. This means that one person may be able to understand speech in a situation where another person has to give up – even when the two people have the same degree of hearing loss and use the same hearing solution. The individual variation in cognitive performance may explain around 30% of the variance, which is observed when a group of people (with similar audiograms) perform a demanding speech-intelligibility-in-noise test (Dryden et al., 2017).

In the simple model shown in Figure 5, the output is either speech understanding (understanding everything without effort spent) or speech understanding with some effort spent (and not necessarily understanding everything). While the model focuses on the important case of speech perception and understanding, it is in principle also valid for other types of signals. In those cases, the ELU part of the model becomes obsolete, but the auditory-object formation and selection parts may still be used to explain the cognitive processes involved – and the listening effort required – when listening to, for example, music.

Obviously, easy (and effortless) formation of auditory objects and implicit processing of speech are the desired working state of the Auditory Cognition element. The Widex Effortless Hearing design rationale (Kuk, 2017), which has been used to guide the development of the most recent Widex hearing aids, attempts to support the cognitive processes (and reduce the listening effort) by providing a clear signal with as few distortions as possible as input to the Auditory Cognition element. This obviously includes appropriate compensation for the deteriorating effects of the hearing loss affecting the Auditory Processing.

Evaluation & Behaviour

The fourth and final element in the framework, Evaluation & Behaviour, is the one that ties the entire framework together. In this element, the listener's perception and cognition of the sound – which in this framework can be regarded as an objective outcome – is paired with the listener's intentions, emotions, circumstances, and the entire context in which the listening takes place. This gives rise to a subjective outcome, which, in its most simple form, may be regarded as a bimodal measure: The listening in a given moment was either satisfactory or unsatisfactory.

The desired state is of course 'satisfactory listening' where the listener gets the desired listening experience, i.e. understanding everything with no effort spent. In this case, no behavioural response is required to improve the listening situation. But when the listening experience is evaluated as being unsatisfactory, the listener may decide to respond to it in order to change and improve the situation, and, accordingly, some kind of change in behaviour is triggered.

As opposed to the previous elements, there are not many existing research-based models that can be used

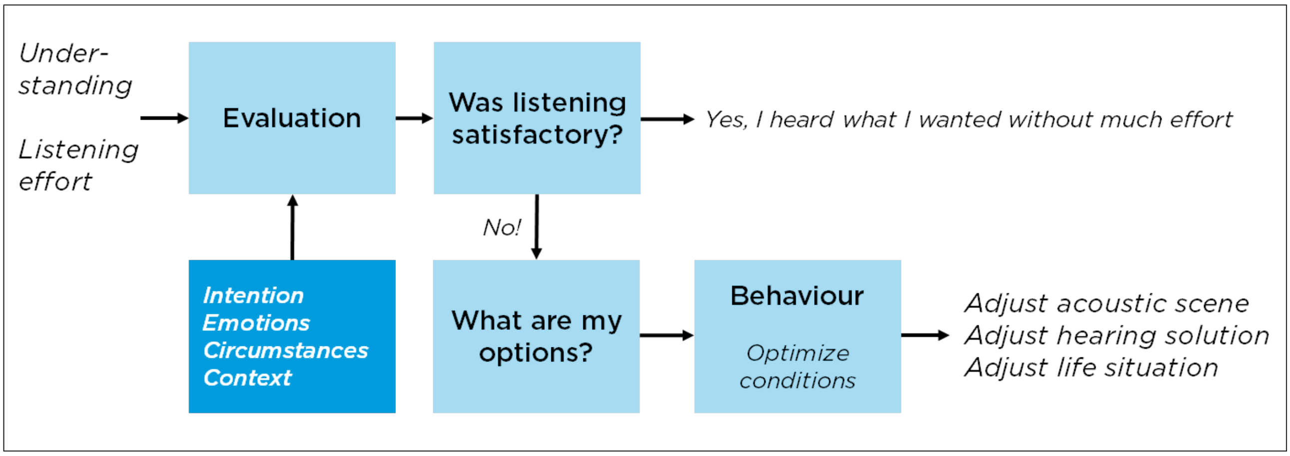

Figure 6. Basic model of the Evaluation & Behaviour element, focusing on speech perception. The input is a level of speech understanding and a level of listening effort.

to explain what is happening within this element. Figure 6 shows an attempt to provide a basic and purely conceptual model of the Evaluation & Behaviour process.

The model illustrates how the listener evaluates the outcome of the Auditory Cognition element – in the figure exemplified by speech understanding (and the listening effort spent in the underlying cognitive process) – based on the listening intention, emotions, circumstances, and the context of the acoustic scene. In practice, these factors are affected by a number of other factors, like personality, previous experience (with a given acoustic scene), expectations, physical and psychological well-being, etc. Thus, the evaluation is a complex and highly individual process, which may vary almost from moment to moment.

For example, if the listener is at a party and intends to understand what the person next to her is saying, and the speech understanding is poor, the listener will most likely respond behaviourally to improve the situation. One solution could be to move closer to the speaker. Another solution (in the case where the listener is a hearing-aid user) could be to change the hearing-aid program or volume setting. However, if the intention was something other than understanding speech (e.g. listening to the music playing), the listener may not perceive the reduced speech understanding as a problem and may therefore consider the listening situation as being satisfactory and choose not to make any behavioural adjustments.

As Figure 1 attempts to indicate graphically, the Evaluation & Behaviour element connects directly back to the Acoustic Scene element. As suggested in the example mentioned above, one behavioural response to the listening experience could be to change the acoustic scene by moving closer to or away from a sound source. The change of the acoustic scene caused by these actions will impact the entire signal path in the hearing flow. This flow may thus be regarded as a continuous loop with frequent changes due to changes in the acoustic scene and/or changes in the listener's behaviour.

The hearing process with the four main elements outlined above provides a conceptual explanation of a listener's short-term perception of, and behaviour in response to, the listening experience in a given moment. However, when the process is repeated multiple times – continuously moving round the closed loop – the sum of different behavioural responses may also be used to explain the longer-term effects of hearing, and, in particular, the effects of hearing loss and hearing solutions on the listener's life. While missing a single word in one loop of the process may have little impact in itself, it may have a substantial impact on, for example, quality of life and perceived handicap if words and sentences are missed repeatedly every day. In this case, behavioural changes may happen on a larger scale, where the listener's entire life situation is affected (as suggested by the last behaviour option in Figure 6). One such change could be to avoid certain types of acoustic scenes in one's everyday life – and another could be to visit a hearing care professional to get help.

FROM HEARING TO REAL-LIFE HEARING

For many years, the audiological focus in the understanding and treatment of hearing loss has been on the right side of the framework shown in Figure 1 – that is, on the Auditory Processing element of the hearing process and its impact on the subsequent Auditory Cognition element. There have been many good reasons for having this focus. To be able to compensate for a hearing loss, it has been – and still is – necessary to understand its physiological origin and its effects on the perception of sound. The fundamental signal processing in all Widex hearing aids and the prescription of gain for a given hearing loss are largely based on this knowledge.

However, while the right side of the framework is obviously essential in order to understand and explain the basics of the hearing process, it does not reflect the fact that hearing is something that happens out in the real world where people live their lives in a multitude of different ways. It is when the perception and cognition of sound meet the listener's intention, emotions, circumstances and context – as described in the Evaluation & Behaviour element – that hearing becomes Real-Life Hearing. Moving the focus from the right to the left side of the framework – to Real-Life Hearing – will impact the way hearing solutions are designed and evaluated.

SUMMARY

In this article, which is the first of two parts, an approach to describing the entire hearing process as a continuous loop consisting of four interconnected main elements is outlined. The framework is built upon a traditional description of the hearing process, where the acoustic sound stimuli are translated to sound perception, but it is extended and tied together by taking the context, circumstances, intentions and emotions of the listener into account in the description of the full process. In this way, the focus is changed from hearing to Real-Life Hearing. This is reflected in the way the Widex hearing solutions are developed as well as in the way they are assessed.

Part 1 of the article provides the background for Part 2, which deals with some of the evidence behind the concept of Real-Life Hearing. Results from some of the research studies done on Real-Life Hearing will be presented, and ways to assess Real-Life Hearing – now and in the future – will be discussed. Furthermore, the challenge of fitting hearing solutions for Real-Life Hearing will be covered – and examples of possible solutions to this challenge will be given by taking a look at some of the new features in the Widex EVOKE™ hearing aid.

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