Oticon Medical BrainHearing – Helping the brain make sense of sound

Technical Report · February 2018

DOI: 10.13140/RG.2.2.36211.43042

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Oticon Medical BrainHearing™ – Helping the brain make sense of sound

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BrainHearing™ is Oticon Medical's guiding star in the development of hearing systems that help the brain make sense of sounds with less effort. We want to help users to invest their cognitive resources in understanding, remembering, interacting, and enjoying, rather than 'just' hearing. We cannot and will not make all situations noiseless and easy, but our solutions should reward the user with increased performance when more effort is put into an important situation.

For the past 20 years, Eriksholm Research Centre has been and continues to be a pivotal voice in the field of cognitive hearing science. Eriksholm plays an integral role in how BrainHearing and the considerations for cognitive effects of hearing loss and deafness have formed the Oticon Medical approach to hearing systems and audiology. The ideas of cognitive processes are more than an overarching goal – they are a guide to how we do research and development, which products we bring to the market, as well as how we verify patient outcomes with the finished solution. Eriksholm works as an inspiration and guide with new methods and measures for testing the effects of the solutions on the cognitive effort and resources of our patients. The strong link to research enables a shorter route from idea to implementation.

To develop solutions that truly help the brain, we need to understand how the listening brain works and how cognitive processes can be supported in the best way possible. This paper gives a background to BrainHearing; what we mean by it, why it is so important to us and your patients, and how it can be measured and quantified. Finally, we review a number of solutions available in Oticon Medical bone anchored and cochlear implant solutions, developed with BrainHearing in mind.

Why BrainHearing™?

- Listening is a complex, cognitive function where multiple processes such as working memory, executive function and attention are at play to achieve a good sound perception.
- Implicit processing allows for easy and effortless understanding of the surroundings. In challenging acoustic environments, explicit processing is needed and more listening effort is expended.
- When effort needs to be put into understanding, the listener must decide if the listening task is worthwhile or should be avoided.
- Most of our listening situations include very varying listening levels and positive signal-to-noise ratios. Hearing solutions must support listening needs in these situations.
- Hearing loss and hearing deprivation has detrimental effects both peripherally and centrally in the brain. Hearing rehabilitation is part of good physical and mental health care.

Understanding the listening brain

Hearing and listening are not the same. We may use the wording interchangeably, but in terms of underlying processes, the two differ. Listening is defined as *hearing with intention and attention* (Kiessling et al., 2003; Pichora-Fuller & Kramer, 2016). Listening thus involves both auditory and cognitive processing. Therefore, mechanisms such as attention, working memory and speed of processing are relevant themes when exploring the topic of listening. Listening begins peripherally, but it actually involves a mosaic of different cognitive functions working together in order to achieve fast and efficient perception of sounds. This ensemble of cognitive functions is called the **listening connectome** (Fig. 1, Kral et al., 2016).

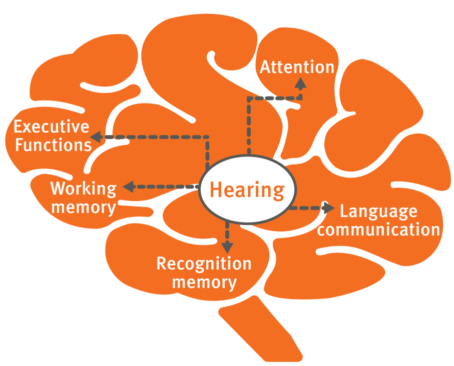


Figure 1.
The mosaic of different cognitive functions working together to achieve fast and efficient sound perception – the listening connectome.

Listening connects hearing with attention and executive functions

In a rich and complex sound environment, the brain must be able to decide what sounds it needs to analyse in more detail. **Attention** is the process that helps us orient cognitive effort towards the information we want to process and retain (Pichora-Fuller et al., 2016; Eckert et al., 2016). This process also engages another type of cognitive ability, called **"executive" functions,** which come into play when our brain has to control and regulate other functions and behaviours.

Listening connects hearing with recognition and long-term memory

When reaching our brain, sounds will be represented and matched to information stored in our **long-term memory,** in order for our brain to make sense of sounds. This process allows us to recognised, auditory objects and recover information about them, such as particular words, or familiar voices.

Listening connects hearing with working memory

Working memory is the ability to retain important information we need to solve daily challenges. It is sometimes called the "blackboard" of our brain (Baddeley, 2012). Some of the information stored in our long-term memory can be used temporarily to solve specific tasks, like for example retaining what someone told you in the discussion, which can be used to facilitate mutual comprehension.

Listening effort and cognitive load

The more complex the acoustic environment becomes, the more these abilities are needed to maintain our listening ability and the more intensively the listening connectome becomes mobilized. Listening will then need important amounts of cognitive energy, and more attention and more working memory resources are needed to maintain efficient processing; listening becomes effortful.

Understanding listening effort

Listening effort is an important and highly relevant measure for quantifying the outcomes of rehabilitation with implantable hearing solutions. Perceived listening effort in everyday tasks is still an issue for hearing aid users, individuals with cochlear implants and individuals with single-sided deafness (Alhanbali et al., 2017).

Listening Effort is described in the context of **Ease of Language Understanding** (ELU) model (Fig.2, Rönnberg et al., 2013). When listening to an acoustic input, the recognition process can use two different pathways. If the acoustic input is clear, as for example when listening in a quiet environment, the auditory representation of the input is clear and can easily be recognized, matched with the representation in long-term memory and understood. In the ELU model, this is the **implicit processing pathway:** access to meaning is fast and automatic, and it is associated with low cognitive effort.

When the listening conditions are made more difficult or complex (or the hearing threshold gets worse), the auditory representation is degraded and does not have an exact match with the stored representation. Due to this mismatch, a secondary pathway comes into play: the explicit processing loop as defined by the ELU model. Instead of instant recognition, the distorted input signal must be compared to information stored in the memory before understanding is possible. This task engages supplementary cognitive resources, mainly the working memory, and is more effortful. If the difficult listening conditions are maintained, listening effort will become more pronounced and may lead to fatigue.

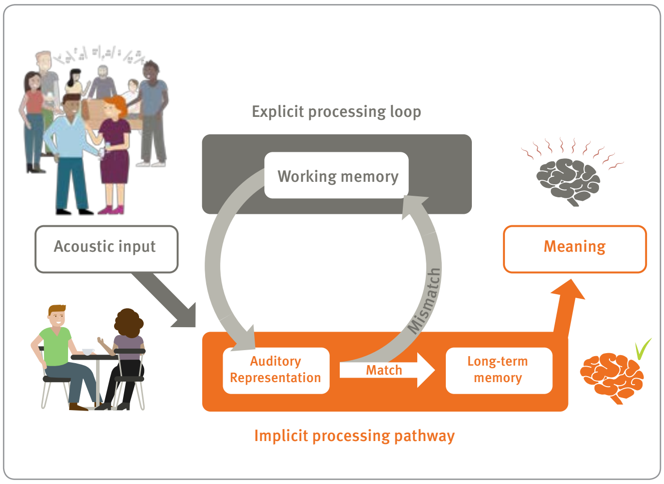


Figure 2.
The ELU model shows how the implicit processing pathway enables fast and automatic processing resulting in low effort, while the explicit processing loop involves more processing and use of working memory resulting in higher load and higher effort (figure adapted from Rönnberg et al., 2013)

As individuals, we have a finite amount of cognitive resources, although this amount varies from person to person and for each individual at different stages of life. This is schematically illustrated for the working memory in Fig 3. Since, within each person the amount of resources is finite, the available resources limit the tasks that can be taken on simultaneously. Cognitive resources can be used to compensate for the hearing difficulties, as described by the ELU model introduced above, up to an individual level. It is for instance well established that having better working memory capacity is associated with better ability to understand speech under adverse conditions as well as better ability to benefit from the advanced signal processing in modern hearing aids (Rudner & Lunner, 2014).

Converging behavioural, pupillometric, and neuroimaging evidence supports the notion that understanding acoustically degraded speech requires added cognitive support and that this cognitive load can affect other operations such as language processing and memory of what has been heard (Peelle, 2017, Lunner et al., 2016). With degraded acoustic input, the brain will experience increased difficulties associating the incoming sound with its representation in memory. Listening becomes more difficult; more processing is needed with increased listening effort as the result.

A key element of BrainHearing™ is to make hearing solutions that support implicit processing as much as possible, in as many situations as possible. To us, continuous focus on using listening effort as an important outcome measure for treatment with hearing solutions is therefore exceedingly important.

Understanding effortful listening

As listening requires increasing effort, the listener must decide if the task is worth the effort – in other words: how motivated is the listener to engage in the situation.

In some situations, the listener will perhaps find that the reward in engaging and participating in communication is so great in form or intellectual or social benefit, that this adds value and increases motivation to stay engaged despite high requirements in terms of effort. In other situations, the listener will be unable or unwilling to sustain the high mental energy to overcome the high level of effort and decide to quit or stop partaking in the activity to avoid becoming fatigued (Pichora-Fuller et al., 2016).

The **Framework for Understanding Effortful Listening** (FUEL) describes how effort may vary with demand and motivation (Fig 4, Pichora-Fuller et al., 2016). Consider an activity that is demanding, for instance because of background noise. Still,

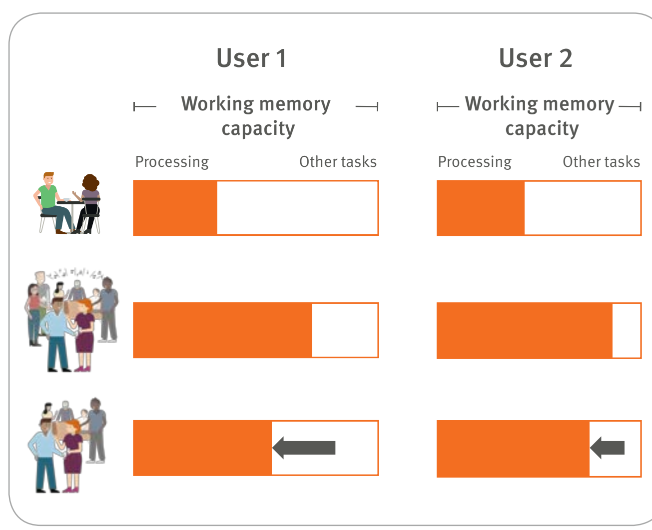


Figure 3.
A schematic illustration showing the effect of inter-individual differences in working memory capacity (left and right panels) suggesting that two individuals, users 1 and 2, may differ in their working memory capacity. For a given task, the allocation of the person's limited capacity for the processing and storage functions of working memory varies with task demands (implicit and explicit processing), from an easy situation (top panel) to a difficult one (middle panel). A hearing system designed based on BrainHearing principles should have the effect of releasing working memory capacity for other tasks (bottom panel). (Adopted from Lunner, 2009).

you are very engaged and your motivation to listen and interact is high. Being in this situation may be effortful, but the effort will be 'worth your while'. However, if the situation worsens e.g. due to even more noise in the environment, tiredness on your part or sudden background music, as illustrated in Figure 4, the situation may become too difficult. That will in turn lower your motivation, and as a result your effort drops – you 'give up'. The decision to give up may be conscious or subconscious.

If this picture persists – if listening during everyday activities often demands more effort than the listener is able and/or willing to put into them – the effect may be stress, withdrawal from social interaction with the associated negative consequences on general health, cognition and quality of life (Pichora-Fuller et al., 2015; Pichora-Fuller et al., 2016).

A second key aspect of BrainHearing™ is therefore to provide added support to the patient when he or she is motivated to expend more effort to be part of a challenging listening environment. That means systems that help out in the situations that matter most, from making the simple ones easier and/or making the difficult ones worth the effort.

Understanding patients' listening needs

What does the everyday sound like? Wagener et al. (2008) set out to study the everyday listening environments of typical hearing aid users. Successful hearing aid users of different ages and social backgrounds were equipped with a recording device and spent four days recording their daily life and sound environments.

A key finding of the study was the vast variation of sound levels within a given situation (Fig 5A). All recordings were categorised by situation and within each category a number of recordings were available and analysed. The overall average sound levels were as expected, however a very large variation of sound levels was found within virtually all situations. This is real life – a quiet situation or a normal conversation might be suddenly interrupted by a door slamming or other background sounds. For successful hearing solutions, these are the everyday situations that must be supported.

Another aspect of importance is the signal-to-noise ratio (SNR) of the different everyday situations (Fig 5B, Wu et al., 2017, Smeds et al., 2015). Wu and colleagues let patients record sound over several weeks, and classified situations using in

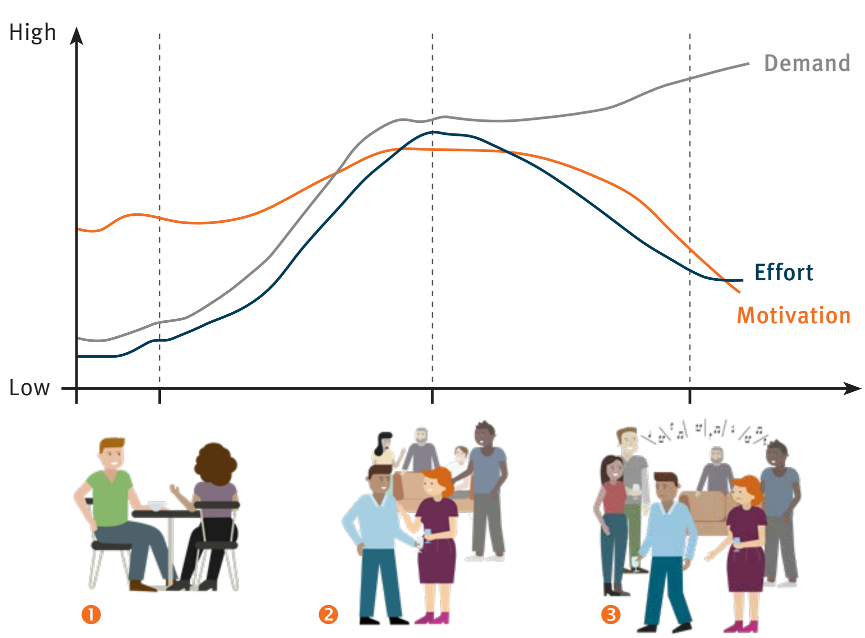


Figure 4.
As demands and motivation may vary, the effort expended may change. Here are three examples:
1) A situation where listening is easy – demands are low and effort is low.
2) The situation is more difficult, however, motivation to listen and participate is high and resultant effort is high.
3) The situation becomes too difficult for listening. Demands are high, motivation to stay in the conversation is low and the effort put into listening is low as well.

situ surveys on smartphones. Speech-plus-noise and noise-only segments were extracted, and the SNRs were estimated. The striking finding in this research is that the vast majority of situations encountered by hearing impaired users have a positive signal-to-noise ratio. Even situations we consider "noisy" still have a positive SNR.

A third key aspect of BrainHearing™ is to focus on the situations that our users in fact are in, sometimes referred to as ecological listening situations. Any hearing solution must support lowering listening effort in positive signal-to-noise-ratios, as well as support listening across varying sound levels.

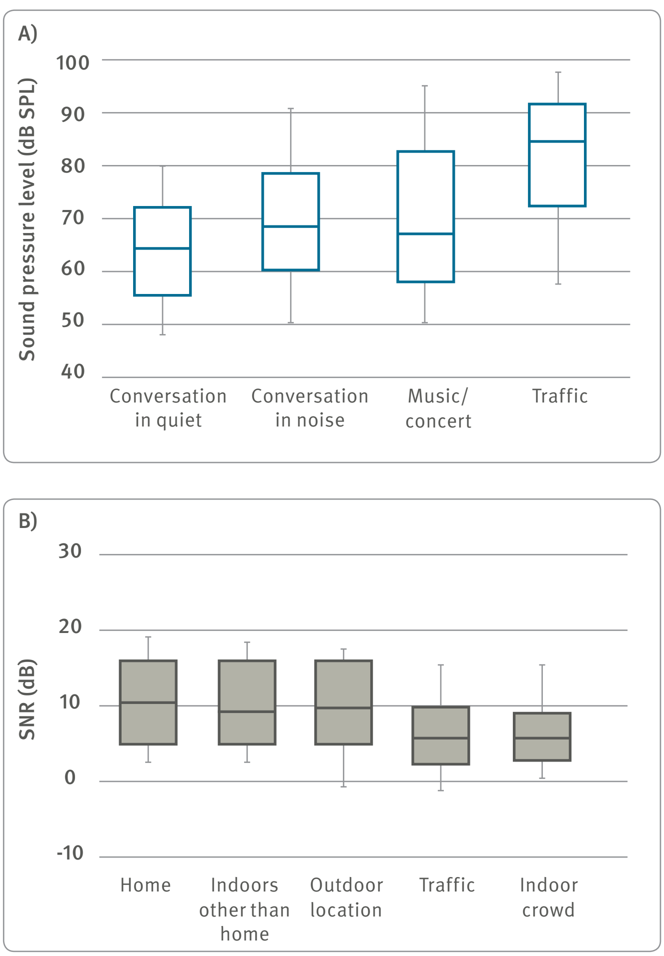


Figure 5.
Analysis of everyday listening situations as a function of listening environment. A (top): Sound levels (subset from Wagener et al., 2008). B (bottom): Signal-to-noise levels (Wu et al., 2017). The boundaries of the boxes represent the 25th and 75th percentile, and the line within the boxes marks the median. Error bars indicate the 10th and 90th percentiles.

Effects of hearing loss

As framed by the listening connectome above, listening begins peripherally, but involves a number of higher level functions. Not surprisingly, the peripheral, physiological defect of hearing loss has neurological, cognitive and psychological consequences.

Use it or lose it?

Brains are plastic throughout life, but during development they are particularly sensitive to external input. Appropriate development of the auditory cortex is largely dependent on sufficient and relevant auditory input. When sound does not reach the auditory areas of the brain, it leaves these neurons devoid of the intended sensory input and neural plasticity phenomena occurs. In the so-called sensitive periods with increased neuroplasticity, the cortex has increased ability to make alterations, either by auditory stimulation or by deprivation. An area being stimulated may take over for a non-stimulated area, thus altering functional connectivity and growth in e.g. the auditory system. Cochlear implants present the potential of ameliorating these deprivation-induced delays.

Over the last decade, Sharma and colleagues have shown how measurements of cortical auditory evoked potentials are different between deaf and hearing children, and how the cortical response can return to normal latencies for some cochlear implanted children, and how age of implantation was a determining factor in this. Evidence of cross-modal re-organisation has been presented as well (Sharma et al., 2015).

Research work has shown for example that auditory attention, auditory working memory or executive functions could be less developed in congenitally deaf individuals (Pisoni & Cleary, 2003; Soleymani et al., 2014; Beer et al., 2014). As a result, deaf children with CI experience difficulties relying on contextual information to ease speech perception and non-literal language comprehension or complex relational concepts formation (Conway et al., 2014; Castellanos et al., 2015). When the hearing loss is congenital, hearing deprivation may furthermore be associated with an impaired development of the listening connectome, leading to limitations in associated cognitive functions and increased listening effort (Geers et al., 2011; Kronenberger et al., 2014).

Also, for conductive and mixed hearing losses, typically treated with bone conducting systems, this should not be underestimated. The effect of periods of sound deprivation in childhood e.g. as seen in children with recurring middle ear disease, have for some time been suspected to have more than the immediate effect of the transient shift in hearing thresholds.

Long-term effects of difficulties in language perception and physiological deficits as well as neural functional changes have been observed (Liberman et al., 2015). In fact, this study displayed a significant reduction in innervation of the inner ear for purely conductive losses that were left untreated in the sensitive period.

Social activity, dementia, and cognitive decline

A steadily growing body of evidence suggests that hearing loss is a main contributor to accelerated cognitive decline and dementia.

Livingston et al. (2017) published a meta study in *The Lancet* that suggested that midlife hearing loss contributed to a 9% risk of dementia. It was the highest single modifiable risk factor identified. Other risk factors included depression and social isolation. Hearing loss and gaining less from social interaction has been proposed to be an added risk in persons with hearing impairment since it contributes to the decrease in social participation and increased isolation.

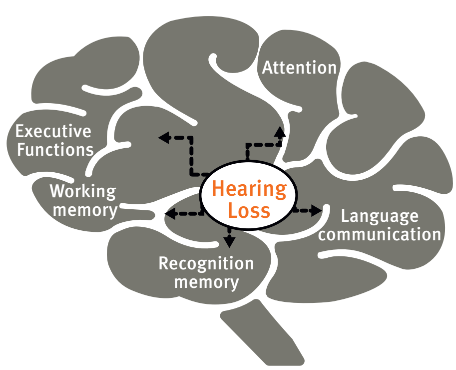


Figure 6.
As framed by the listening connectome, hearing loss has far-reaching consequences beyond the physiological effect of peripheral hearing loss.

Lin and colleagues presented strong evidence of the association between untreated hearing loss and dementia in the Baltimore Longitudinal Study of Aging (Lin et al., 2011). Later findings showed that individuals with hearing impairment, compared to normal hearing, showed accelerated declines in brain volume (Lin et al., 2014).

Across a span of 25 years, a cohort of over 3,500 individuals was followed and seen for regular testing of cognitive, social and functional areas (Amieva et al., 2015). The study found an association between self-reported hearing loss and cognitive decline. Elderly adults with hearing problems not using hearing aids saw greater and faster cognitive decline, while those with hearing loss using hearing aids had similar rates of cognitive decline as those with no hearing impairment. In the field of hearing implants, cochlear implantation was shown to improve cognitive abilities and positively influence social activity and quality of life in a group of 94 patients aged 65 to 85 years with postlingual hearing loss (Mosnier et al., 2015). Cochlear implantation could have a potential beneficial effect on executive functions in elderly patients (Sonnet et al., 2017). These observations suggest that by improving communication abilities, hearing solutions may help improve mood, increase social interactions, and enable participation in cognitively stimulating abilities and consequently could slow cognitive decline. Similar results where poorer hearing was associated with cognitive impairment were found in different populations of older adults in the US and Germany (Kiely et al., 2012; Fritze et al., 2016; Gurgel et al., 2014).

Treatment of hearing loss is not only about hearing; it is even more important than that. Hearing care is an essential part of keeping you physically and mentally healthy for an active and rewarding life. A last aspect of BrainHearing™ is delivering hearing solutions that people will use to keep cognitively fit.

Measuring how sound processing supports the brain

The aim with providing an implantable hearing solution to a deaf or hearing impaired individual is of course to increase audibility. But this is not the sole aim. A goal must be to help alleviate listening effort and mental strain. Therefore, outcomes of rehabilitation with implantable hearing solutions must include relevant indicators for cognitive processes and effort.

As described earlier the task of listening is composed by an acoustic challenge based on the acoustic input and the hearing acuity of the listener, which interacts with the cognitive demand of the situation and motivation of the individual. The resultant listening effort can be observed using a measure of behaviour, neuroimaging, or physiological responses (Fig. 7 inspired by Peelle, 2017).

Behavioural tests can assess recall or storage in working and long-term memory, using the principles of the ELU model (Fig 2) and the individual working memory capacity (Fig 3). Research has shown how these cognitive functions are affected by e.g. choice of sound transmission for bone anchored hearing or help systems in hearing aids (Lunner et al., 2016; Ng et al., 2015). Using the Sentence-Final Word Identification and Recall test (SWIR), researchers have been able to show how direct sound transmission bone conduction solutions have a significant effect on ability to recall words relative to solutions where sound is being dampened by transmission through the skin – even when speech intelligibility is identical with the two solutions and close to 100 %. The degradation in sound delivery has a significant effect on the ability to recall what is heard.

Pupillometry is becoming a well-recognised way of measuring listening effort (Zekveld et al., 2010; 2011). Ample evidence shows that pupil response is sensitive to the transient, task-evoked, and involuntary effort in response to e.g. the task of listening to speech and noise. The sympathetic pupil response is sensitive to processing load and changes to this load (Zekveld & Kramer, 2014). Thus, pupil dilation reflects the changes in mental effort associated with a given task. The more challenging the task, the larger the pupil dilation. Different parameters in the response show different concepts or mechanisms. Peak pupil dilation is related to momentary load, while resting pupil diameter before and after the task or presentation indicates the individual's engagement level.

In neuroimaging, measures of EEG activity have been trialled to show listening effort. Here increasing level of e.g. the alpha response has been linked to the neural substrates of increased cognitive effort. EEG has shown listening effort differences between hearing aids with and without help systems enabled (Bernarding et al., 2017). Use of functional near-infra-red spectroscopy (fNIRS) as an imaging method has been trialled to get insight into the functional organisation of the brain and how it is altered by deafness and, subsequently, by cochlear implantation (McKay et al., 2016).

In the world of hearing instrument research, pupillometry has been used to show how new technology or features are able to help relieve effort (Wendt et al. 2017), both for challenging and easy tasks. Adding to this, pupillometry has been used to show the variation in listening effort and speech understanding over a range of listening tasks (Ohlenforst et al., 2017, Fig 8). Recent research shows that, even in situations with close to ceiling performance on the speech understanding task, pupillometric data showed a difference in the effort expended with amplification only and amplification and help systems for hearing impaired listeners (Wendt et al., 2017).

This makes the strong case of the obtainable, measurable improvement with advanced signal processing – even in what could be categorised as easy listening situations.

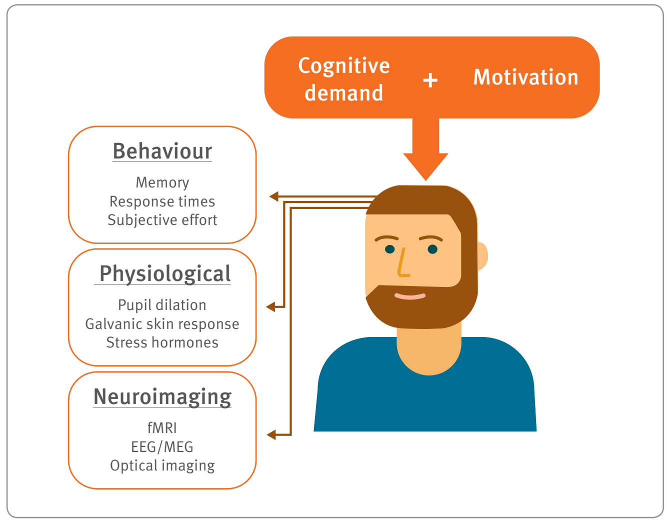


Figure 7.
Listening effort is affected by multiple variables; hearing acuity, acoustic input, cognitive demand of the situation and motivation of the individual. Listening effort for a given task can be observed using measures of behaviour, neuroimaging, or physiological responses (Inspired by Peelle, 2017).

Supporting BrainHearing in Oticon Medical Hearing Implants

BrainHearing is our guiding star when developing products and sound processing. We strive to support implicit processing as much as possible in as many situations as possible. Therefore, a number of aspects must be addressed when developing technology. Sometimes the same underlying solution will help both CI and BAHS users, like the Free Focus feature. Sometimes the same considerations lead to different solutions, simply because the technical options and limitations are different for two systems.

BrainHearing guides which bone conduction solutions we develop

BrainHearing has directed our overarching bone conduction product strategy in a very concrete way: Oticon Medical develops implantable solutions with direct sound transmission only, i.e. solutions where the transducer acts directly on the bone. This is the case with a Ponto sound processor on an abutment, and that is what we will keep developing in the future for transcutaneous solutions. We will however not make implants that build on the so-called skin drive principle (Reinfeldt et al, 2015), where the vibrations are transferred through the skin to the bone.

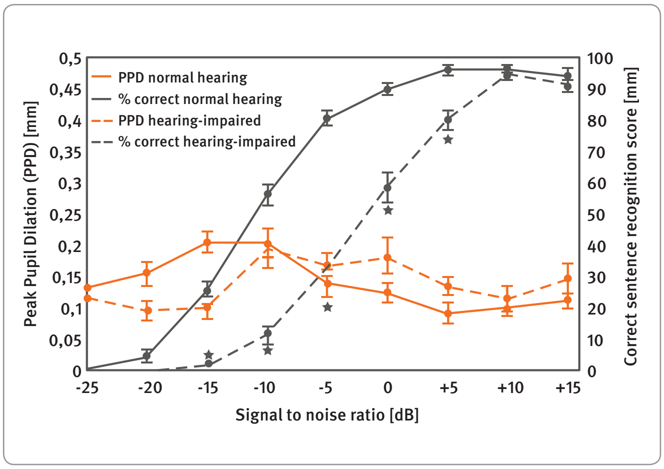


Figure 8.
Speech intelligibility (right y-axis) and peak pupil dilation (left y-axis) indicating the effort associated with listening in speech to noise ratios. Solid lines show results obtained for individuals with normal hearing. Dotted lines show results obtained for hearing impaired individuals (Figure adapted from Ohlenforst et al., 2017, Hearing Research). In new research, pupillometry has been used to show the effect of advanced signal processing on listening effort.

The reason lies in the BrainHearing principles. When comparing the two methods of transmission, a sound processor on an abutment allows the users to recall significantly more than with the same solution using skin transmission (Lunner et al., 2016) and Figure 9. Such results confirm our firm belief in the need for an active, direct sound transmission. When submitting to a surgically implanted hearing solution, the outcome with this solution should not be subpar, but one that supports speech understanding that is as effortless as possible.

To maintain clarity of speech as well as of other sounds, a hearing device needs to handle the huge dynamic range present in everyday listening situations. This is a key technical aspect of bone anchored devices needed to support implicit listening and the natural sound quality the Ponto family of sound processors is known for.

For bone conduction devices, unlike acoustic or electrical stimuli, a main limitation is in fact the maximum output the device can deliver. Even the most powerful BAHS devices cannot produce a maximum output above patients' upper comfortable level (UCL). Once the maximum output is reached, loud sounds will be distorted. In other words, the dynamic range of the incoming sound is not faithfully reproduced. A more powerful sound processor, with a higher maximum output level provides access to a larger dynamic range of sound, keeping more of the loud sounds undistorted. This is why the maximum output of the device can be directly linked to the perceived sound quality. With the Ponto 3 SuperPower, we have delivered the world's first abutment level sound processor that combines a significantly higher maximum output with a small design. Research clearly shows that a large range of users, not only those with the largest mixed hearing losses, but also milder ones can benefit (Bosman et al., 2018). In fact, based on the BrainHearing principles we argue that all bone anchored users would benefit from a SuperPower device, due to the improvements in maximum output and therefore signal integrity. To utilise the resulting dynamic range best, Ponto sound processors use SpeechGuard, designed to maintain the amplitude variations between sounds and preserve the

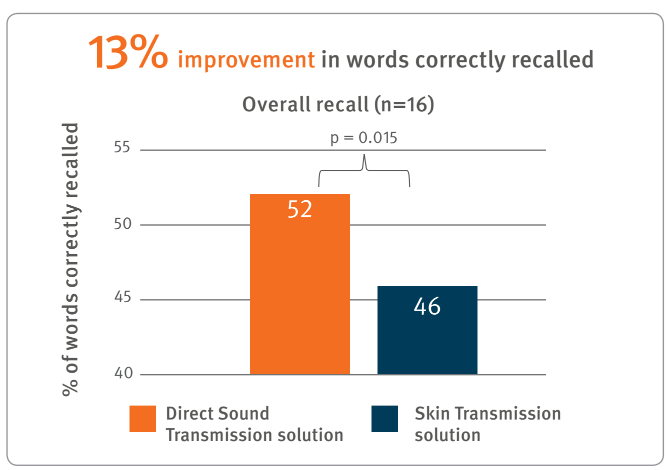


Figure 9.
Recall of words was significantly better with direct sound transmission compared to skin drive, despite speech intelligibility being the same (Lunner et al., 2016). The results were measured in a blinded balanced cross-over design, using Ponto Plus Power sound processors, and including soft band correction on the skin transmission condition.

natural details and nuances of speech and everyday sounds (Sockalingham, 2015).

A third manifestation of BrainHearing principles in the Ponto 3 family is the Free Focus directionality system, which we share with the Neuro cochlear implants. We now know that it matters how speech is understood – even when speech intelligibility tests show you understand 100%. Using that insight, Free Focus is the result of focusing on helping in the "easy" situations, which happen to make up 70% of the typical users' everyday situations.

Neuro – the world's first cochlear implant designed on BrainHearing principles

Users of cochlear implant systems have a special need for hearing implants that prioritise conveying the clearest signals to the brain, in order to make sense of sound in the easiest way possible. The BrainHearing principles allowed Oticon Medical to design a cochlear implant system that takes into account the way the brain processes sounds so that users can make the most out of their journey towards hearing restoration.

One of the main challenges when considering direct electrical stimulation of the auditory nerve is to maximise information transfer to the brain, while not overloading the nervous system. The first ingredient of neural stimulation is the electrical pulse that is used to trigger the auditory nerve response. Most CI systems use biphasic symmetric pulses, consisting of two successive phases of current alternating in polarity. This pulse shape has two major disadvantages: a low power-efficiency caused by the need to generate current for each phase, and a double excitation of the auditory nerve fibre as both phases have the power to trigger physiological responses. Moreover, the neural system reacts differently to both phases. Biphasic symmetric pulses are thus causing a spatial and temporal smearing of the stimulation (Shepherd & Javel, 1997; 1999; Rattay et al., 2001). The Neuro CI system limits physiological overload and generates clearer neural signals by using an industry-unique, pseudo-monophasic pulse with passive discharge. This pulse is made of a first active, power-consuming anodic phase, selectively stimulating the auditory nerve (e.g., Macherey et al., 2008), followed by a passive charge balancing phase. During this phase, all non-stimulating electrodes of the electrode-array are turned to capacitive mode. This electrical stimulation is thought to provide a cleaner way of evoking auditory responses in the auditory system.

Another way to optimise information transfer to the brain is to avoid overloading the ascending pathways with too much information or information that is redundant. The BrainHearing principles here question the idea that more information is always better. It seems on the contrary that too much information can overload hearing systems and that sometimes too much information will lead to excessive listening effort and reduced performance. A clear example here is stimulation rate. Faster stimulation rates can lead to increased crosstalk between electrodes (Middlebrooks, 2004). The Neuro system therefore delivers stimulations at an optimised stimulation rate of 500 Hz by default and with a maximum value of 1 kHz, in order to avoid entering into the refractory period of the nervous system thereby limiting causing unnecessary extra load and cognitive effort. Research has shown that with today's available stimulation strategies, low stimulation rate around 500 Hz had some clear advantages for certain CI users, especially in difficult listening situations (Brochier et al., 2017). With a fully flexible peak-picking strategy, offering an adjustable n-of-m parameter over the whole stimulation range (from 1 to 20 peaks per stimulation frame), the Neuro 2 sound processor allows very precise adjustment of the stimulation density to suit each and every CI user's needs.

When considering sound analysis, the Neuro 2 combines a very wide functional input dynamic range (IDR – 83 dB SPL), with an adaptive, multiband output compression system to maximize audibility in all listening situations and ensure that fine acoustic details of speech are preserved. In order to account for the limited dynamic range (DR) a CI can deliver, other systems usually rely on a dual-stage signal processing strategy with an adaptive Front-End automatic gain control (AGC), associated with an instantaneous, Back-End static compression. Front-End AGCs can however introduce some distortions into the signal (Moore, 2008). The goal of Voice Guard, an adaptive multiband output compression system, is to perform both stages in only one step placed at the end of the signal processing pipeline, thereby reducing distortions and increasing intelligibility compared to dual-stage strategies (Langner et al., 2017; Segovia Martinez et al., 2016).

Ultimately, we want to enable users to participate and keep up a socially active and engaged lifestyle. The hearing solution must work in the everyday situations experienced by the user. Listening effort, and thus fatigue, accumulates during the course of the day. Improvements must be sought for the majority of listening situations. The graded directionality options of Free Focus (including split directionality and full directionality) accommodate noisy environments, maintaining speech intelligibility even in the most challenging listening conditions. But the most common situations are the ones with a good signal-to-noise ratio. With that in mind, the Free Focus directionality system was developed, available in both Neuro 2 and the Ponto 3 family.

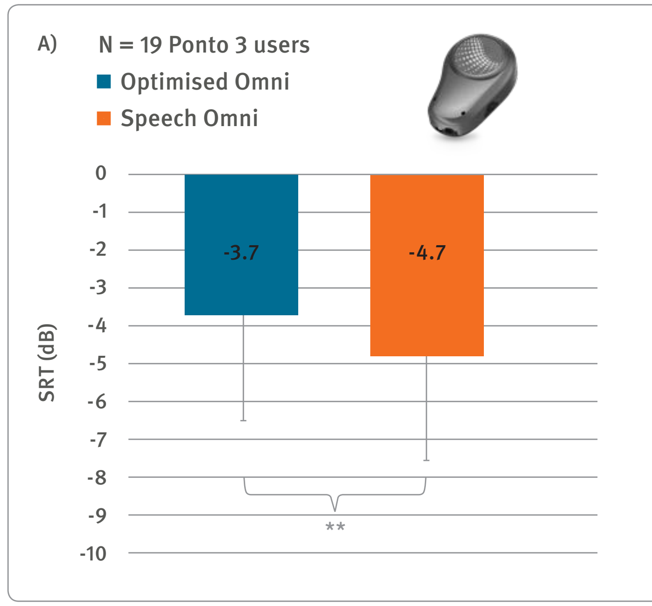
Free Focus includes Speech Omni, an improved omnidirectional mode offering better speech understanding in the situations that are most encountered by users.

In a study of Speech Omni in the Ponto 3 family, speech intelligibility in noise was improved by 15% compared to using the previous generation of Ponto sound processors (Ågren et al., 2018). Users spend most of their time in situations, around 70%, where Speech Omni is automatically activated. When the first Neuro CI patients were evaluated (Figure 10), we observed an advantage for the Speech Omni feature over Optimised Omni mode, improving phoneme recognition by 12 percentage points in a first group of 6 Neuro users (clinical evaluation ongoing).

The Free Focus feature is therefore an excellent example of BrainHearing-guided development: delivering better speech understanding the majority of the time supports our dedication to making listening easier and in turn helps the brain make sense of sound.

Summary

BrainHearing™ is much more than an overarching philosophy; it concretely guides the type of solutions we develop at Oticon Medical. How we do research and development is tangibly affected by the attention to optimal outcomes for the listening brain. Likewise, we continue to test our solutions against measures of listening effort, cognitive resources and mental energy. We are far from finished today. We can however promise that, with every new generation of Oticon Medical products, we take a further step towards definite BrainHearing: a hearing solution that makes the process of listening as effortless as possible for our users in their everyday lives and listening environments, supporting an active and rewarding social life.



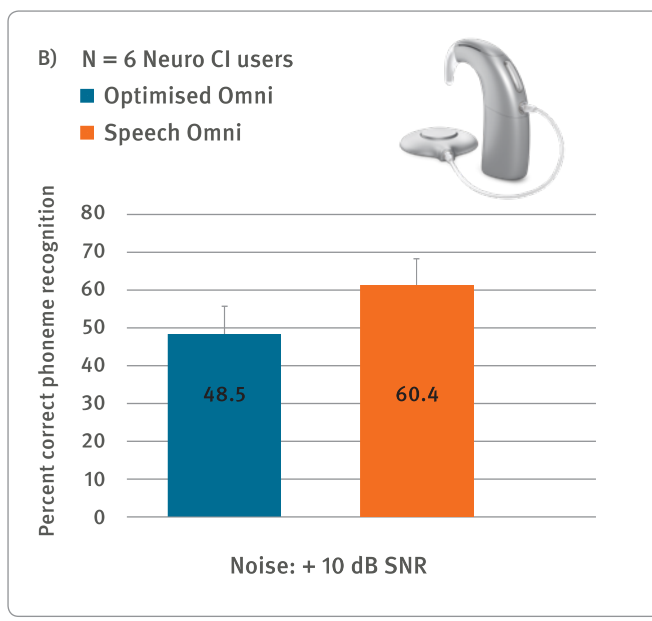


Figure 10 A&B.
A) Data from bone anchored users of Ponto 3 (Ågren et al., 2018)
B) Preliminary data on the improvement using Speech Omni for a group of six Neuro CI users. Clinical investigation in progress.

References

Alhanbali S, Dawes P, Lloud S, et al. (2017). Self-Reported Listening-Related Effort and Fatigue in Hearing-Impaired Adults. Ear & Hearing, 38, e39–e48.

Amieva H, Ouvrard C, Giulioli C, et al. (2015). Self-Reported Hearing Loss, Hearing Aids, and Cognitive Decline in Elderly Adults: A 25-Year Study. J Am Geriatr Soc., 63, 2099-104.

Baddeley A. (2012). Working memory: theories, models, and controversies. Annu Rev Psychol., 63, 1-29.

Beer J, Kronenberger WG, Castellanos I, et al. (2014). Executive functioning skills in preschool-age children with cochlear implants. J Speech Lang Hear Res., 57, 1521 - 1534.

Bernarding C, Strauss DJ, Hannemann R, et al. (2017). Neurodynamic evaluation of hearing aid features using EEG correlates of listening effort. Cogn Neurodyn., 11, 203-215.

Bosman A, Kruyt I, Mylanus E, Hol M and Snik A. (2018). Evaluation of an Abutment-level SuperPower Sound Processor for Bone-Anchored Hearing. Clin Otolaryngol, Submitted.

Brochier T, McDermott HJ & McKay CM. (2017). The effect of presentation level and stimulation rate on speech perception and modulation detection for cochlear implant users. J Acoust Soc Am., 141, 4097.

Castellanos I, Kronenberger WG, Beer J, et al. (2015). Concept formation skills in long-term cochlear implant users. J Deaf Stud Deaf Educ., 20, 27-40.

Conway CM, Deocampo JA, Walk AM, et al. (2014). Deaf children with cochlear implants do not appear to use sentence context to help recognize spoken words. J Speech Lang Hear Res., 57, 2174 - 2190.

Eckert MA, Teubner-Rhodes S & Vaden KI Jr. (2016). Is Listening in Noise Worth It? The Neurobiology of Speech Recognition in Challenging Listening Conditions. Ear Hear., 37, 101S - 110S.

Fritze T, Teipel S, Óvári A, et al. (2016). Hearing impairment affects dementia incidence. An analysis based on longitudinal health claims data in Germany. PLoS One, 11, e0156876.

Geers AE, Strube MJ, Tobey EA, et al. (2011). Epilogue: factors contributing to long-term outcomes of cochlear implantation in early childhood. Ear Hear., 32, 84S - 92S.

Gurgel RK, Ward PD, Schwartz S, et al. (2014). Relationship of hearing loss and dementia: a prospective, population-based study. Otol Neurotol, 35, 775–81.

Kiely KM, Gopinath B, Mitchell P, et al. (2012). Cognitive, Health, and Sociodemographic Predictors of Longitudinal Decline in Hearing Acuity among Older Adults. The Journals of Gerontology, 67, 997 - 1003.

Kiessling J, Pichora-Fuller MK, Gatehouse S, et al. (2003). Candidature for and delivery of audiological services: Special needs of older people. Int J Audiol, 42(Suppl 2), S92–S101.

Kral A, Kronenberger WG, Pisoni DB, et al. (2016). Neurocognitive factors in sensory restoration of early deafness: a connectome model. Lancet Neurol, 15, 610-621.

Kronenberger WG, Beer J, Castellanos I, et al. (2014). Neurocognitive risk in children with cochlear implants. JAMA Otolaryngol Head Neck Surg, 140, 608-615.

Langner F, Gnansia D, Hoen M, Büchner A, & Nogueira W. (2017). Effect of dynamic range in different stages of signal processing in Cochlear Implant listeners on speech. ENT World Congress, IFOS 2017, June 24-28th, Paris, France.

Liberman MC, Liberman LD & Maison SF. (2015). Chronic Conductive Hearing Loss Leads to Cochlear Degeneration. PloS One, 10, e0142341.

Lin FR, Metter EJ, O'Brien RJ, et al. (2011). Hearing Loss and Incident Dementia. Arch Neurol, 68, 214 – 220.

Lin FR, Ferrucci L, An Y, et al. (2014). Association of Hearing Impairment with Brain Volume Changes in Older Adults. Neuroimage, 15; 90: 84–92.

Livingston G, Sommerlad A, Orgeta V, et al., (2017). Dementia prevention, intervention, and care. Lancet, pii: S0140-6736(17)31363-6.

Lunner T, Rudner M, Rönnberg J. (2009). Cognition and hearing aids. Scand J Psychol., 50(5):395-403.

Lunner T, Rudner M, Rosenbom T, et al. (2016). Using Speech Recall in Hearing Aid Fitting and Outcome Evaluation Under Ecological Test Conditions. Ear Hear, 37 Suppl 1: 145S - 154S.

Macherey O, Carlyon RP, van Wieringen A, Deeks JM & Wouters J. (2008). Higher sensitivity of human auditory nerve fibers to positive electrical currents. J Assoc Res Otolaryngol., 9: 241-251.

Middlebrooks, JC. (2004). Effects of cochlear-implant pulse rate and inter-channel timing on channel interactions and thresholds. J. Acoust. Soc. Am. 116, 452–468.

McKay CM, Shah A, Seghouane AK, et al. (2016). Connectivity in Language Areas of the Brain in Cochlear Implant Users as Revealed by fNIRS. Adv Exp Med Biol, 894: 327-335.

Moore BC. (2008). The choice of compression speed in hearing AIDS: theoretical and practical considerations and the role of individual differences. Trends Amplif., 12: 103-112.

Mosnier I, Bebear JP, Marx M, et al. (2015). Improvement of cognitive function after cochlear implantation in elderly patients. JAMA Otolaryngol Head Neck Surg, 141, 442 - 450.

Ng EH, Rudner M, Lunner T, et al. (2015). Noise reduction improves memory for target language speech in competing native but not foreign language speech. Ear Hear, 36, 82 - 91.

Ohlenforst B, Wendt D, Lunner T, et al. (2017). Impact of SNR, masker type and noise reduction on listening effort as indicated by the pupil dilation. Poster presented at CHSCOM 2017.

Pisoni DB & Cleary M. (2003). Measures of working memory span and verbal rehearsal speed in deaf children after cochlear implantation. Ear Hear, 24, 106S-120S.

Peelle JE. (2017). Listening Effort: How the Cognitive Consequences of Acoustic Challenge Are Reflected in Brain and Behavior. Ear Hear, Sep 21, doi: 10.1097/AUD.0000000000000494.

Pichora-Fuller MK, Kramer, SE, Eckert, MA, et al. (2016) Hearing Impairment and Cognitive Energy: The Framework for Understanding Effortful Listening (FUEL) Ear & Hearing 2016;37;5S–27S).

Pichora-Fuller MK, Mick PT & Reed M. (2015). Hearing, cognition, and healthy aging: Social and public health implications of the links between age-related declines in hearing and cognition. Semin Hearing, 36, 122 - 139.

Pichora-Fuller, MK, Kramer, SE, Eckert, MA, et al. (2016). Hearing Impairment and Cognitive Energy: The Framework for Understanding Effortful Listening (FUEL). Ear Hear, 37 Suppl 1, 5S - 27S.

Rattay F, Lutter P & Felix H. (2001). A model of the electrically excited human cochlear neuron. I. Contribution of neural substructures to the generation and propagation of spikes. Hear Res., 153: 43-63.

Reinfeldt, S, Håkansson, B, Taghavi, H, Eeg-Olofsson, M. (2015). New developments in bone-conduction hearing implants: a review. Medical Devices. Evidence and Research. 8; 79-93.

Rönnberg J, Lunner T, Zekveld A, et al. (2013). The Ease of Language Understanding (ELU) model: theoretical, empirical, and clinical advances. Front Syst Neurosci, 7, 31.

Segovia-Martinez M, Gnansia D & Hoen M. (2016). Coordinated Adaptive Processing in the Neuro Cochlear Implant System. Oticon Medical White Paper. (Link Oticon Medical Website).

Sharma A, Campbell J, & Cardona G. (2015). Developmental and cross-modal plasticity in deafness: Evidence from the P1 and N1 event related potentials in cochlear implanted children. Int J Psychophysiol, 95, 135–144.

Shepherd R & Javel E. (1997). Electrical stimulation of the auditory nerve. I. Correlation of physiological responses with cochlear status. Hear Res., 108:112-144.

Shepherd RK & Javel E. (1999). Electrical stimulation of the auditory nerve: II. Effect of stimulus waveshape on single fibre response properties. Hear Res., 130: 171-188.

Sockalingham R. (2015). Minimizing Signal Distortion through a Novel Amplification Scheme in Bone Anchored Sound Processors. Oticon Medical White Paper.

Smeds, K, Wolters, F, Rung, M. (2015). Estimation of Signal-to-Noise Ratios in Realistic Sound Scenarios. J Am Acad Audiol, 26, 183 - 196.

Soleymani Z, Amidfar M, Dadgar H, et al. (2014). Working memory in Farsi-speaking children with normal development and cochlear implant. Int J Pediatr Otorhinolaryngol, 78, 674 - 678.

Sonnet MH, Montaut-Verient B, Niemier JY, et al., (2017). Cognitive Abilities and Quality of Life After Cochlear Implantation in the Elderly. Otol Neurotol, 38, e296-e301.

Wendt D, Hietkamp RK, & Lunner T. (2017). Impact of Noise and Noise Reduction on Processing Effort: A Pupillometry Study. Ear Hear, 38, 690 - 700.

Wu, Y-H, Stangl, E, Chipara, O, Hasan, Welhaven, A, Oleson, J. (2017) Characteristics of Real-World Signal to Noise Ratios and Speech Listening Situations of Older Adults With Mild to Moderate Hearing Loss. Ear&Hearing. August - volume publish ahead of print.

Zekveld AA, Kramer SE, & Festen JM. (2010). Pupil response as an indication of effortful listening: the influence of sentence intelligibility. Ear Hear, 31, 480 - 490.

Zekveld AA, Kramer SE, & Festen JM. (2011). Cognitive Load During Speech Perception in Noise: The Influence of Age, Hearing Loss, and Cognition on the Pupil Response. Ear Hear, 32, 498 - 510.

Zekveld AA, & Kramer SE. (2014). Cognitive processing load across a wide range of listening conditions: insights from pupillometry. Psychophysiology, 51, 277-284.

Ågren J, Rosenbom T, Holmberg M. 2018, in preparation. Ponto 3 FreeFocus – The art of improving everyday listening. Oticon Medical White Paper. (Data available in Oticon Medical report no 34425-00).

Because sound matters

Oticon Medical is a global company in implantable hearing solutions, dedicated to bringing the magical world of sound to people at every stage of life. As a member of one of the world's largest groups of hearing health care companies, we share a close link with Oticon and direct access to the latest advances in hearing research and technologies. Our competencies span more than a century of innovations in sound processing and decades of pioneering experience in hearing implant technology.

By working collaboratively with patients, physicians and hearing care professionals, we ensure that every solution we create is designed with users' needs in mind. We share an unwavering commitment to provide innovative solutions and support that enhance quality of life for people wherever life may take them. Because we know how much sound matters.

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183434UK / 2018.02

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