WHITEPAPER
2020

BrainHearing™

The new perspective

ABSTRACT

BrainHearing is the guiding star for the research and technological development at Oticon and is our philosophy to help the brain to make sense of sound by understanding how the brain works. In this whitepaper, we discuss the new scientific discovery in how the brain processes sounds. Recent evidence suggests that there are two subsystems in the auditory cortex. In the early stage of sound processing, referred to as the Orient subsystem, the entire auditory scene is represented in the brain. In the later stage, referred to as the Focus subsystem, the brain selectively processes and amplifies the sound in focus. It connects further to other brain regions that are responsible for different cognitive functions and processes. This suggests that the brain needs the entire sound scene for natural processing. The new perspective in BrainHearing sheds lights on how hearing loss should be treated and provides us with valuable insights into defining the next step of hearing care.

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Introduction

Our brains understand the world around us through our five senses. We heavily rely on our hearing in everyday life for communication. Having a hearing loss does not only mean listening becomes difficult, but the brain also needs to work harder to understand sounds. Our BrainHearing vision is to deliver technologies that optimally support the natural processing of sounds in the brain, such that it is given the best possible conditions to perform and to make sense of sound. New scientific discoveries have unveiled further knowledge of how the brain processes sound, and this serves as the foundation of the new perspective in BrainHearing.

The Brain – Our Natural Sound Processor

Our brain's exceptional ability to make sense of our environment has baffled scientists for a very long time. For example, take a scenario where you are standing amongst a crowd appreciating the energetic performance of street musicians. You notice the mellow notes of the cello, to the uplifting and dynamic chords of the saxophone, or even the annoying barking of the dog (Figure 1).

You appreciate the music, while occasionally tuning into a specific instrument and switching to another at will. Why can the brain focus on the instrument of interest, while simultaneously shutting out the barking? An intuitive assumption would be a "spotlight effect". In fact, this has been the consensus for a long time. This assumption, however, could not explain why hearing aid users still struggled despite using directional microphones. Surely if we can cut out everything except for the intended sound source, the listener would hear what they wanted easily?

The answer is not as simple, as this assumption ignores a key player – our brains.

A Sound's Journey from Ear to Brain

As it turns out, the brain can act as its own sound processor. In order for it to work optimally, the brain requires all relevant information it needs to achieve its ultimate goal of producing a response relevant to the context it is in. To better understand how we filter out and selectively attend to certain sounds, one must dive deep into the individual processes that occur in the brain. Generally, the full soundscape first enters the ear and is converted into chemical-electrical energy inside the cochlear nerves. This chemical-electrical energy forms the **Neural Code** and is then relayed to the brain through the auditory nerves, the brainstem and finally the cortex.

Crucially, despite the impressive processing power of our brains, it is a limited resource (Rönnberg et al., 2013). The brain cannot exhaustively scrutinise every sound in the environment most of the time. For this reason, the brain needs to select an object to examine in greater detail, at the cost of other objects. This is object selection and it causes the cello notes to "stand out", such that you can better tune into its melody.

The process of forming and selecting objects is divided into the **Orient** and **Focus** subsystems or stages. Ultimately, these sounds are recognized by the brain as meaningful objects relevant to the context we are in. Figure 2 illustrates the typical journey of a sound to the cortex.

Figure 1. Listening to the music in a highly dynamic environment

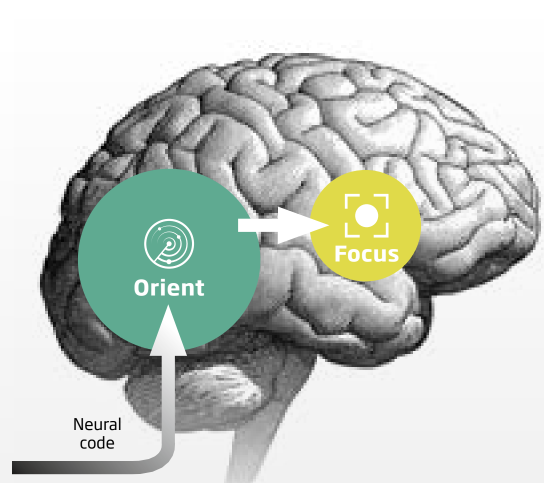

Figure 2. The two hearing subsystems: Orient and Focus

Orient – The Full Sound Picture in the Primary Auditory Cortex

As a sound mixture is funneled into the ear, the cochlea converts mechanical vibrations into electrical energy, which forms the **Neural Code** that travels through the auditory nerve into the brainstem, finally reaching the primary auditory cortex. This is where auditory objects are formed (O'Sullivan et al., 2019). In this region, the neurons inside the brain are activated in such a way that it represents the full soundscape, with music, speech and noise included.

Studies of selective attention have investigated how an entire sound scene is represented in the brain. The entire sound scene typically includes an attended sound and unattended sound(s). Using different brain imaging techniques such as Magnetoencephalography (MEG), Electroencephalography (EEG) and Electrocorticography (ECoG), studies have demonstrated that the neural representations of all sounds in the entire sound scene were equally represented in the early-stage process within the primary auditory cortex (O'Sullivan et al., 2019; Puvvada & Simon, 2017). In other words, the brain has not attended to any specific sound object just yet. Instead, the brain is searching for acoustic features that contain relevant information and places them all on the table with a birds-eye view. This is synonymous to placing all the tools from a toolbox on the table before choosing what you need (Figure 3, left panel). After collecting all this information, the brain can move on to selecting which of the tools (i.e. object) it wants to pick, depending on the goal of the listener.

We refer to this early-stage processing in the primary cortex as the **Orient** stage. In this stage, the brain relies on a good **Neural Code** to create an overview of the sound objects and begin separating sounds to determine what is going on in its surroundings, to create the full sound scene. In the above scenario, the musical instruments and the barking are just as apparent to the brain for now. This information provides the prerequisites to **Focus**.

Focus – Selective Attention in the Non-Primary Regions of the Auditory Cortex

After objects are formed in the **Orient** stage, it is now time to select, depending on what the listener would like to focus on. In this stage, object selection takes place. Take the previous example where you want to focus on the cello. Your brain realises from the previous stage that the cello (a low-pitched musical instrument) has a deeper tone than the saxophone (a higher-pitch instrument). It will then use the distinguishing features (low versus high pitch) to figure out those are in fact different sound sources. This is a case of the brain identifying a *feature* (i.e. pitch) that *best distinguishes* between the instruments or other objects (Figure 3, right panel). In contrast, if the two instruments had the exact same pitch, the brain will simply search for another feature that distinguishes between them, such as the difference in the rhythm or the direction sounds are coming from. To tell between the cello and barking noise, the brain recognises that the barking has a different rhythm to the music, as barking starts and stops abruptly, whereas music tends to be more continuous, thus separating the two objects from each other. This searching of features would not have been possible if we listened like a spotlight.

By picking out these unique features, the selected object inherently becomes strongly represented at this later-stage process, occurring in the non-primary regions of the auditory cortex. This is what is demonstrated by the same researchers, who have found through selective

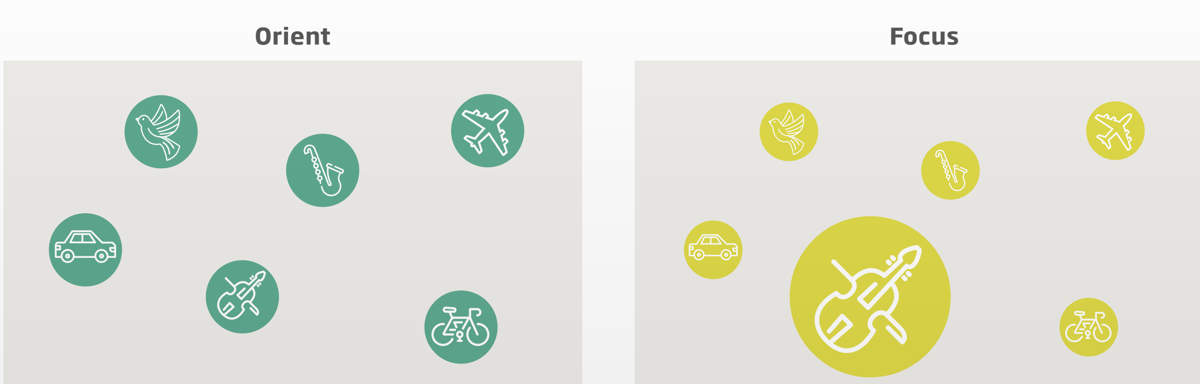

Figure 3. (Left panel) The representation of the full sound picture in Orient. (Right panel) The object of focus (the cello) is much strongly represented in Focus

attention studies that the attended sound source is much better represented in this later stage (O'Sullivan et al., 2019; Puvvada & Simon, 2017; Alickovic et al., 2020, for an overview see Ng & Man, 2020). In contrast, the representation of unattended sound sources is not as well encoded here in non-primary auditory cortex as they were in the primary auditory cortex. Since the selected object stands out from other sounds, this supports efficient and effective processing for higher-level processes. Allowing for example speech understanding to happen without overloading the processing capacity of the brain.

This later auditory processing stage in the non-primary regions is hereby referred to as the **Focus** stage. In this stage, the brain identifies the sound it wants to focus on or switch attention to, while the irrelevant sounds are filtered out. This stage also allows us to sustain our attention on a sound source over long periods of time, with research demonstrating that our focus of an object becoming clearer over time due to sustained attention (Elhilali et al., 2009). To switch attention, our brains scan the ignored part of the environment as fast as four times a second (Helfrich et al., 2018) just in case there is something else that may be of interest to us.

Put together, our brains are constantly trying to make sense of sounds in the environment. In order to achieve that, the brain needs to distinguish between sound features and their corresponding sources. The two stages, **Orient** and **Focus**, work together simultaneously and continuously to find and enhance cues that best segregate sound sources. This iterative refinement of the **Neural Code** for the brain allows us to make sense of sounds that are of interest to us in our everyday conversations, particularly when there is noise.

BrainHearing – the framework

By combining the processes introduced above and cognition, we have an overview of how sounds are processed and interpreted from the ear to the brain. (see Figure 4)

1. **Hearing and the Neural Code** – this stage involves the most peripheral parts of the auditory system (i.e. the ear). Sound is received in the form of mechanical energy and converted into the **Neural Code** such that the brain can make sense of it (Shinn- Cunningham & Best, 2008). This **Neural Code**, containing acoustic features of sounds, can influence the subsequent stages, depending on its fidelity.

2. **Orient and Focus** – the next step happens primarily in the auditory cortex, the region in the brain specialised in identifying and separating sounds. This step can be further subdivided into **Orient** and **Focus** stages. The **Orient** stage is where the full sound picture is represented (object formation) in the brain. The **Focus** stage is where selective attention acts (object selection), enhancing the perception of the object that is of interest.

3. **Recognize** – this is a stage where the brain makes use of available working memory to make sense of sound. In this stage, the brain extracts meaning and controls complex cognitive processes such as speech understanding, attention switching and memorisation. This stage also receives and integrates information from other senses such as visual input.

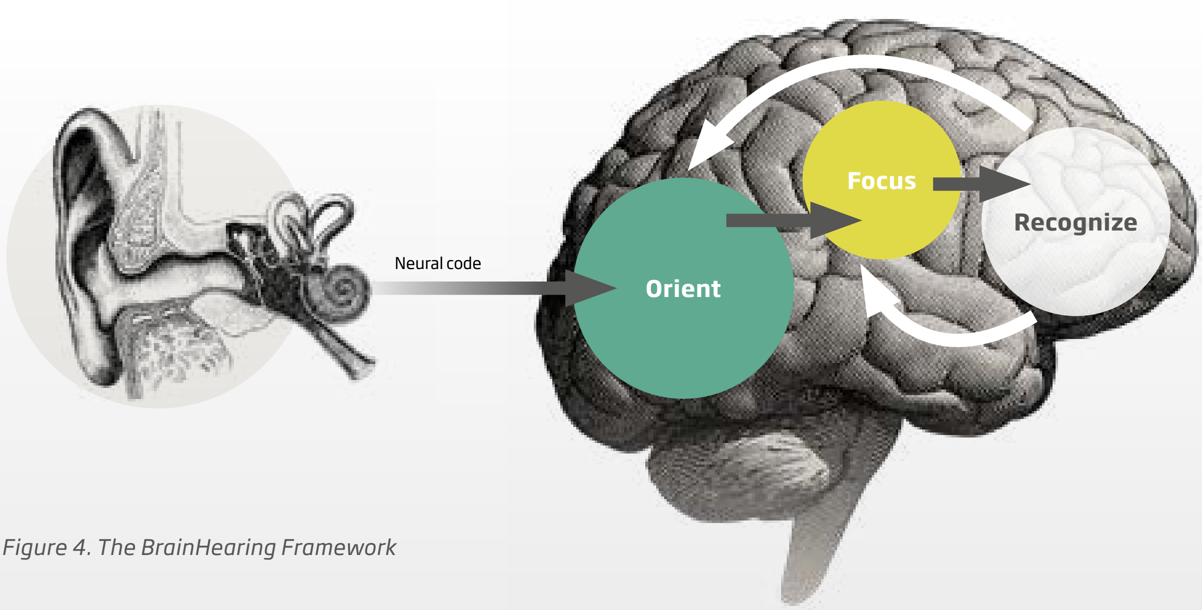

Figure 4. The BrainHearing Framework

By looking at the framework, we can now see that good sound quality representing the full sound picture is a prerequisite to supporting successful speech comprehension and communication. This is because a **Neural Code** of higher fidelity can make the subsequent stages of **Orient**, **Focus** and **Recognize** much easier. These cognitive abilities are closely related to communicative abilities in real life situations, as demonstrated by a strong relationship between cognitive measures and speech understanding in numerous studies (Dryden et al., 2017; Lunner & Sundewall-Thorén, 2007).

Hearing Loss – not just an ear problem

What happens if the listener has a hearing loss then? We can take our learnings from the BrainHearing framework to predict what would happen to a hearing-impaired listener in our example of the musical instruments:

Due to hearing loss, the quality of sounds entering the ear is low, resulting in a low-fidelity **Neural Code**. As the listener may not be able to hear the details in the sound e.g. the treble of the saxophone, some of the distinguishing features of each sound source are now blurry, making it difficult for the brain to examine the object of focus. As a result, the brain will need to allocate additional cognitive resources in the form of working memory to make sense of it (Rönnberg et al., 2013). This increased demand of mental resources is demonstrated by an increase in listening effort (Edwards, 2016), eventually leading to a break-down in communication.

However, the collateral impact of hearing loss does not just stop there. Additional mental resources for hearing means less resources for other cognitive processes such as sustained attention and attention switching (Rönnberg et al., 2013).

In fact, considerable changes to the internal structure of the brain have been observed in hearing-impaired individuals (Lomber et al., 2020). For example, scientists demonstrated that the auditory cortex of hearing-impaired individuals were more responsive to visual stimuli, revealing a recruitment of the auditory regions by visual ones in contrast to normal hearing peers (Campbell & Sharma, 2014, Stropahl and Debener, 2017). Outside the auditory cortices, emerging scientific evidence also reveals that other portions of the brain such as the frontal regions are recruited for auditory processing, indicating an additional allocation of resources from other brain regions to process sounds in hearing-impaired individuals (Peelle et al., 2011, Wingfield & Peelle, 2015).

Thus, this recruitment of other brain networks provides us with ample evidence that even mild to moderate hearing loss may lead to changes of the brain's internal integrity (Campbell & Sharma, 2014).

Building from changes in the functional structure of the brain, it has also been observed that individuals with age-related hearing loss also display an accelerated decline in the volume of auditory cortical regions, particularly the primary auditory cortex where **Orient** takes place, as well as changing integrity of auditory white matter and grey matter (e.g. Lin et al., 2014) which are responsible for communication between brain cells. These have heavy implications for the cognitive ability of listeners, especially its decline (Loughrey et al., 2018). In fact, age-related hearing loss has been shown to have significant associations with cognitive impairment, decline and dementia (Barnes & Yeffe 2011; Albers et al., 2015). Aiming to explore how dementia can be prevented , a life-course model that incorporates risk factors associated with dementia was proposed by Livingston and colleagues (2017; 2020), describing how possible

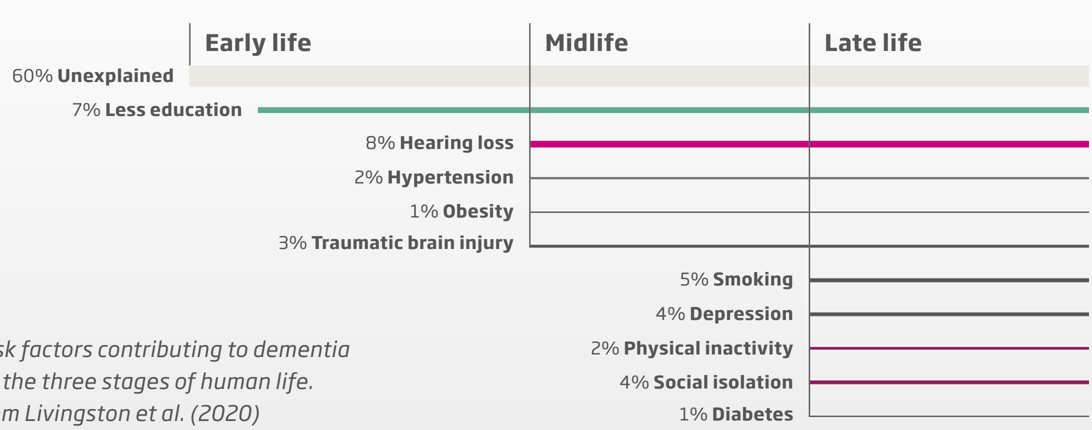

Figure 5. Risk factors contributing to dementia throughout the three stages of human life. Adapted from Livingston et al. (2020)

conditions that arise throughout the three stages of an individual's lifetime may lead to an increased risk of developing dementia.

Figure 5 demonstrates that hearing loss is a considerable risk factor of dementia, even when compared to other commonly researched factors such as depression, social isolation, smoking, and physical inactivity. Additionally, this risk is exacerbated by increasing severity of hearing loss (Lin et al., 2011). One may notice that hearing loss, depression, physical inactivity, and social isolation can form a vicious cycle with each other. If a person experiences hearing loss, they will likely start to experience increased listening effort and social gatherings become challenging to them. This may cause them to withdraw from social interactions and physical activity to avoid distress and lead to them feeling more socially isolated. As a result of extended periods of social isolation, depressive symptoms may start to develop as they cannot find connection with people around them. Finally, due to the contributions of all the risk factors, dementia becomes an increasingly likely outcome.

What can we do?
We can now see that hearing loss has far reaching consequences that extend from the ears to our brain. What can we do about this?

A recent study published by Glick and Sharma (2020) examined how regular usage of well-fitted hearing aids may benefit users. Using neuroimaging techniques, they revealed an increased recruitment of the auditory cortex by vision. That is, whereas the visual cortex was the clear player when observing visual cues in normal hearing, the auditory cortex started to react as well in the hearing-impaired brain. Subsequently, the authors fitted the hearing -impaired individuals with hearing aids and carried out the same measurements after 6 months of usage. Figure 6 illustrates the results.

The illustration shows that the regions which were active before hearing aid usage have now reverted to levels which are more similar to what was observed in those with normal hearing. As a result, we can see that there is a degree of recovery as shown in the brain with hearing aids usage.

The cause-effect relationship between hearing aid use and dementia is still under investigation. Importantly however, hearing loss is a modifiable risk factor (Livingstone et al., 2017, 2020), meaning there are ways to treat it such that it can reduce the likelihood or delay the development of dementia or cognitive decline (Dawes, 2019; Maharani et al., 2018). For instance, Livingstone et al. (2020) encourages use of hearing aids for hearing loss and protection of ears from excessive noise. This is further supported by recently reported benefits to cognitive performance by hearing aids (e.g. Karawani et al., 2018).

Normal hearing | **Hearing loss** | **After hearing aid use** (6 months)

Brain activity while **seeing**

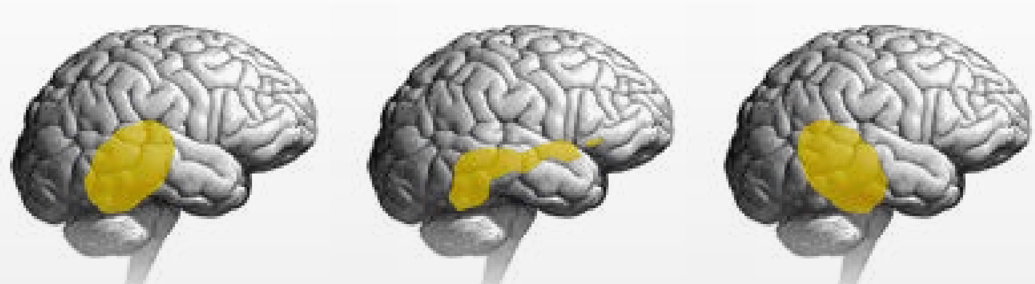

Figure 6. Hearing aid usage of 6 months helps reverse cortical reorganization. Adapted from Glick and Sharma (2020)

Conclusions

We have discussed how sound is processed in the brain, that it first processes the entire auditory scene in **Orient,** and then the attended sound is selectively processed and amplified in **Focus**. This is where selective attention takes place and connects to other brain regions for different cognitive functions and processes such as recognizing, remembering, and responding. This suggests that the brain needs the entire sound scene for natural processing.

The unifying BrainHearing framework that incorporates theories of auditory objects, selective attention and cognition to provide us with a much deeper understanding of not just how the brain makes sense of sound, but also how we can optimise this process for a better listening experience for hearing aid users.

Oticon follows the BrainHearing philosophy of understanding hearing loss – we view the impacts of hearing loss not just from the ear, but also from the perspective of the brain - where sounds find meaning. Our evidence has consistently demonstrated how the BrainHearing technology can benefit speech understanding (Le Goff et al., 2016), listening effort and recall by freeing up cognitive resources in challenging listening situations (Juul Jensen, 2019). Furthermore, the BrainHearing Technology is also supported by evidence showing benefits observed directly inside the brain, such as selective attention (Ng & Man 2020).

Hearing loss degrades the quality of sounds entering the brain and is known to be related to different health conditions at older age. The new perspective in BrainHearing highlights the need of a Neural Code of high fieldity of the full sound picture in treating hearing loss. Together with optimal fitting and regular use of hearing aids, this provides us with valuable insights into defining the next step of hearing care. As we step into the future, we are focusing on new, exciting discoveries that will further add to the complete picture of BrainHearing.

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