WHITEPAPER
2021

# Oticon More™ competitive benchmark

## Part 1 – Technical evidence

ABSTRACT

This whitepaper describes the results of technical measurements comparing the performance of Oticon More to that of two high-end competitor hearing aids. Output signal-to-noise ratio measurements obtained in real-life sound scenes demonstrate that the MoreSound Intelligence™ feature in Oticon More provides a larger contrast between speech and the background than the two tested competitors in such complex listening situations, giving the user better access to speech in the listening environment, even when it comes from the side. With a detailed time-frequency analysis of the hearing-aid output, we show that the action of the deep neural network in Oticon More, combined with the precise amplification of the MoreSound Amplifier™, conveys speech details with more precision than technologies using traditional directionality, noise reduction, and compression approaches. Finally, the results show that Oticon More adapts faster to newly encountered sound scenes than the two tested competitors, thus enabling the user to benefit from increased speech understanding more rapidly as their sound environment changes. Part 2 of this competitive benchmark will report results of a user listening test comparing the same three hearing aids.

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## More meaningful sound for the brain

Giving the brain access to more sound is what Oticon More's innovative approach to audiology aims to achieve by challenging the limitations of conventional approaches to directionality, noise reduction, compression, and feedback management (Santurette & Behrens, 2020). For more sound to really make a difference for a person with hearing loss, we cannot simply pass on all sound entering the hearing aid to the user and turn up the gain. This would be ignoring the complexity and individuality of each person's hearing loss and would fail to provide audibility, clarity, and comfort. Modern hearing aids thus need to provide more of the sound that matters for each user and to adapt their sound processing to each person's hearing abilities and listening needs, making sure that they get the help they need in listening situations that they find most challenging. Achieving this means that, ideally, hearing aids should improve the neural activity at the early stages of auditory processing in the brain so that this neural code resembles that of a normal-hearing person (Lesica, 2018). With accurately restored neural input, the processing of auditory information in the brain will be eased and more successful, making it easier to recognize important sound features and orient through the complex auditory scenes it encounters. This is an important pre-requisite for selective attention to be directed towards the sounds that are in focus at any given moment, while still keeping aware of other important sounds in the scene (Man & Ng, 2020).

The MoreSound technologies in Oticon More were designed to come one step closer to that goal by providing more meaningful sound to the brain, with proven BrainHearing™ clinical benefits such as a clearer representation of the full sound scene and important individual sounds in the auditory cortex, enabling the user to better focus on relevant sounds and better understand and remember what is being said with less listening effort (Santurette et al., 2020). First, MoreSound Intelligence (MSI) and its embedded deep neural network (DNN) clarify the full sound scene to make meaningful sounds stand out from the background, based on a careful match between an ongoing analysis of the incoming sound scene the needs of the user in that situation. Then, the MoreSound Amplifier (MSA) ensures that the access to important sound details is preserved while amplifying the sound. For more details about the audiology and features of More, see Santurette & Behrens (2020) and Brændgaard (2020a,b).

So how does the MoreSound approach in More compare to the latest premium technologies that use a combination of front-facing directionality, speech-focused noise reduction, and fixed-resolution compression? To find out, we obtained binaural recordings of the output of Oticon More and compared them with the output of two of the latest premium competitor devices on the market (referred to as Competitor A and Competitor B in the following) for the exact same input. While performing this technical evaluation, we put emphasis on bringing sound scenes from real life into the lab, allowing us to evaluate the performance of the different hearing aids in situations reflecting what users experience in their everyday life. We investigated the technical performance of Oticon More in terms of three outcome measures:

- The achieved contrast between speech and the background in real-life complex environments, using output signal-to-noise ratio (SNR) measurements;
- The preservation of important speech details in the presence of noise, using spectrogram analysis and an objective speech intelligibility metric;
- The speed of adaptation of the hearing aids in attenuating background noise as they encounter a new sound scene.

## Making speech stand out in complex environments

While modern hearing aids have kept improving their signal processing strategies to make speech stand out, understanding conversations in busy sound environments remains one the most commonly reported difficulties for people with hearing loss, and providing sufficient help to users in complex situations is still a domain demanding further improvements (Picou, 2020). Social environments are, by nature, dynamic. You may want to follow the story of your friend in front of you, but in a group conversation, you may also want to be aware when another member of the group chimes in, all of this without being disturbed by irrelevant noise and without feeling left out from ambient sounds around you.

Hearing aids provide assistance to users in such complex environments by attenuating the interfering noise and/or amplifying important sounds such as speech. This contrast between a target signal and background noise can be quantified by the signal-to-noise ratio (SNR) at the output of the hearing aids. A large output SNR is desirable as it indicates a significant contrast between the signal we want to focus on and the background noise. In other words, a high output SNR makes speech more accessible to the brain.

Measuring the output SNR has become an increasingly common procedure to study how different algorithms, features, or devices technically compare in noisy environments (Naylor & Johannesson, 2009). Generally, artificial lab setups are used for this purpose, where a pre-recorded target and noise signal is played back by single loudspeakers from specific directions. In this study, we wanted to take this measurement technique one step further by investigating how our hearing aids performed in realistic scenarios typically experienced by hearing-aid users. For this purpose, we used two 3D-audio scenes recorded in real life with a spherical microphone array that captures sound from every direction. The first scene was a café scene with a single Danish male talker located either 15° or 60° to the right as the target sound (see Figure 1 for an illustration) in a 71-dB-SPL background of people chatting, cutlery noise, and other café sounds such as a coffee machine running. The second scene was a busy lunchroom scene with two Danish male talkers having a conversation as the target sounds, located at 25° to the left and 15° to the right, respectively (see Figure 2 for an illustration), in a 75-dB-SPL background of people chatting and lunchroom sounds such as cutlery noise. Note that the talker locations were kept as they were in the real café and lunchroom scenes. The two scenes were played back in a sound studio equipped with 29 loudspeakers, of which 16 were placed in the horizontal plane, 6 at a lower elevation, 6 at a higher elevation, and 1 right above the centre of the array. With that many loudspeakers arranged spherically, the 3D sound scenes could be played back using ambisonic reproduction, precisely re-creating the real sound field at the centre of the array, with a feeling of being directly in the real scene for a listener placed in this sweet spot (Favrot & Buchholz, 2012).

To capture the performance of the hearing aids, a head-and-torso simulator (HATS) was placed in the sweet spot and fitted with the different test hearing aids using dedicated ear moulds with minimal venting to ensure that the recorded sound had been processed by the hearing aids. All hearing aids were adjusted to the respective manufacturer's maximum recommended settings for very complex environments (MSI set to provide most help for Oticon More and directionality and noise reduction set to the maximum recommended settings for the two competitors) and gain was provided based on a sloping moderate hearing loss (N3 standard audiogram, Bisgaard et al., 2010) using each manufacturer's proprietary rationale. While playing back the two real sound scenes mentioned above, the output of each of the hearing aids was recorded by the highly sensitive microphones at the end of the HATS' ear canals. By obtaining recordings for different phase relationships between the target signal and the noise, the output SNR provided by each hearing aid was computed using the phase-inversion method established by Hagerman & Olofsson (2004). For more details about this technique, see also Lesimple (2019). The output SNRs were weighted with the Speech Intelligibility Index (SII) to reflect the contribution of different frequency regions to speech understanding. For each sound scene, these SII-weighted output SNRs were calculated from output signals of the HATS without hearing aids (here referred to as "unaided"), wearing Oticon More, and wearing hearing aids from Competitors A and B.

Figure 1 shows the obtained output SNRs in the café scene. In this sound scene, the talker is located towards the right, such that the right ear is advantaged in terms of SNR compared to the left ear due to the acoustic head shadow effect. This means that the listener needs only to listen with the right ear receiving the less noisy signal to benefit from the largest acoustic contrast between the speech and the background (Avan et al., 2015). This is commonly referred to as the "better ear" effect (e.g., Rana & Buchholz, 2018, Bronkhorst & Plomp, 1988). The lighter-colored, full-height bars in Figure 1 show the output SNR for the better ear for each of the measured conditions. When the target talker is at an angle of -15° (left side of Figure 1), Oticon More, with 2.5 dB SNR, is on par with Competitor A (2.4 dB) and surpasses Competitor B (1.4 dB) in terms of improving the contrast between speech and the background. When the target talker is moved further to the side at an angle of -60° (right side of Figure 1), More becomes the only hearing aid among those tested to provide a clearly positive SNR (2.0 dB), whereas Competitor A (0.3 dB) and Competitor B (-0.7 dB) do not provide clear access to speech any longer.

Oticon More thus provides the needed contrast for speech to stand out from the background regardless of whether the talker is located towards the front or towards the side of the listener, while the narrow beamformers of Competitors A and B act like invisible walls in the sound scene, blocking out speech that does not precisely face the listener. While users in such a situation are most likely to rely on their better ear, what if we now consider the extreme case in which the listener would rely equally on cues from both ears? As indicated by the average output SNRs across ears (darker-colored bars in Figure 1), Oticon More would still outperform both competitors in such a situation.

What if the user is now in a group conversation, for example sitting across from two friends at a table in a busy restaurant? Figure 2 shows the output SNR obtained with the different hearing aids for the measured lunchroom scene in which the target signal consists of two talkers. As there is speech on both sides of the listener, the average SNR across ears is shown. In such a situation, Oticon More still provides the most contrast between speech and the background (4.7 dB SNR) compared to either Competitor A (4.2 dB) or B (2.6 dB). When more than one talker is present, Oticon More thus also provides a larger contrast between speech and noise to better support users following conversations that involve more than one person.

In summary, Oticon More provides an overall larger contrast between speech and the background in real-life complex sound scenes than the two tested competitors, especially as the talker moves off to the side. With MSI and the action of its embedded DNN, More is able to give better access to speech around the user than the combination of traditional noise reduction and narrow directionality approaches to handling noise that block out sounds not coming directly from the front. When the user needs help, More makes the speech stand out more from both frontal and lateral directions, without the need to face the talking person very precisely.

## Providing access to speech details in noise

In order to achieve good speech understanding in noise, not only does the speech need to clearly stand out from the noise, it is also crucial that the fine details of speech elements are conveyed to the user as accurately as possible by the hearing aid. Without access to these details, the user will have to fill in the gaps and guess more of what is being said, leading to additional use of the brain's cognitive resources and thereby more effortful listening.

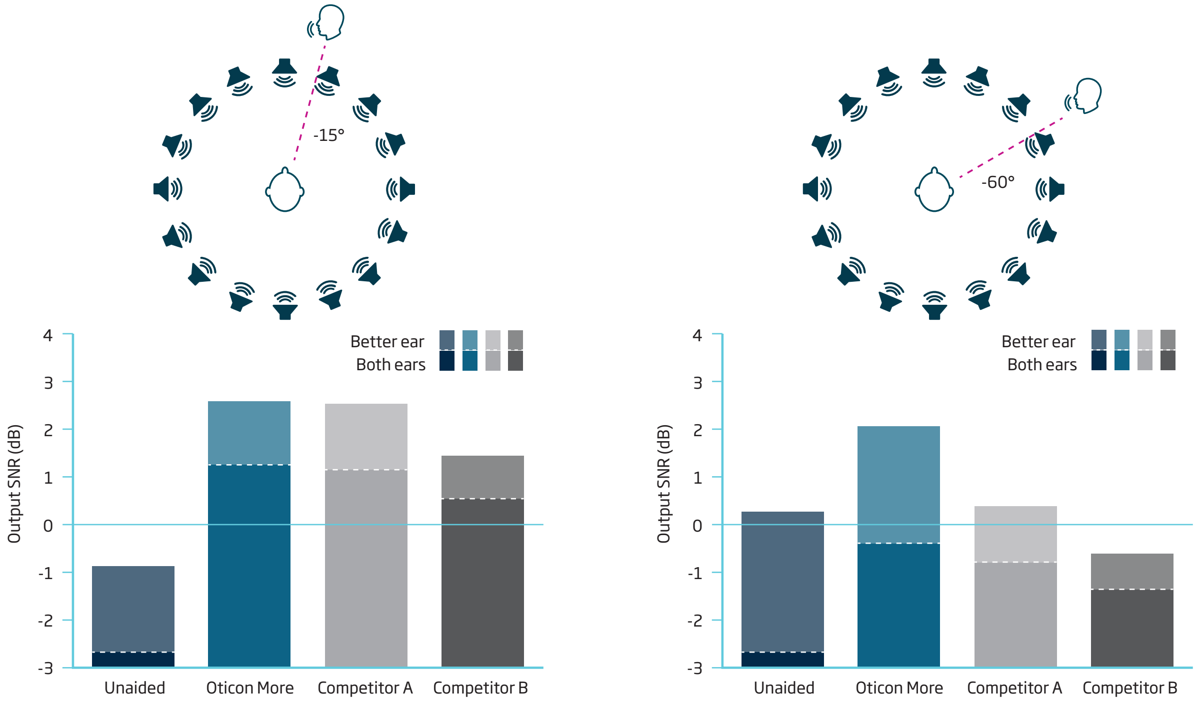

*Figure 1: Schematic illustration of talker positions and SII-weighted output SNRs in dB measured in the café scene. Left: Target talker positioned at -15° azimuth. Right: Target talker positioned at -60° azimuth. The lighter-colored, full-height bars show the right (better) ear SNRs and the darker-colored bars show the average SNRs across ears.*

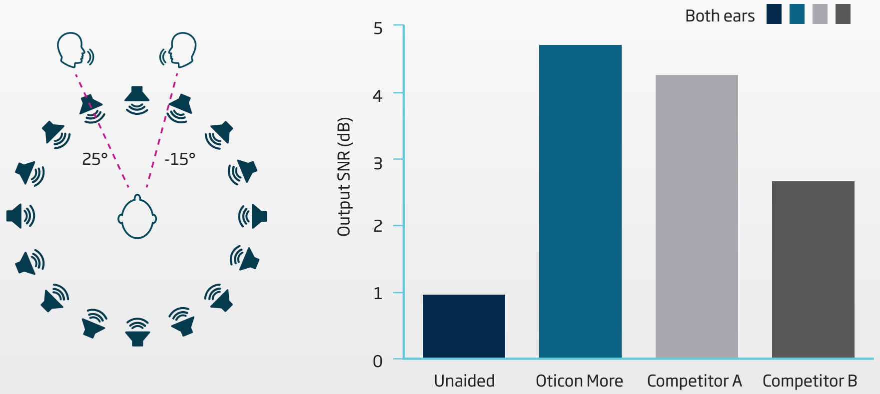

*Figure 2: Schematic illustration of talker positions and SII-weighted output SNRs in dB measured in the lunchroom scene.*

The preservation of speech details can be studied by carrying out a detailed time-frequency analysis of the hearing aid output and comparing it to the clean speech input. Such an analysis can be illustrated in a spectrogram. A spectrogram is a visual representation of the distribution of sound power, usually measured in dB, into frequency components of a time-varying audio signal, such as speech. It is used extensively in the fields of linguistics, speech processing, audio and music, and of course hearing science. A spectrogram is commonly depicted as a heat map which shows time on the horizontal axis, frequency on the vertical axis, and the magnitude of sound power at a particular frequency and time by varying the color or the brightness of each point in the image.

Figure 3 shows an example of such a spectrogram for a clean speech signal, in this case a 9-second sequence of Danish sentences from the Dantale II corpus (Wagener et al., 2003) recorded in one unaided ear of a HATS manikin. The horizontal axis shows time progressing from left to right in seconds. The vertical axis shows frequency in logarithmic scale, increasing upwards from 125 Hz to 10 kHz. The sound power magnitude is represented by brightness variations in the image, where dark regions indicate low sound power (quiet areas) and bright regions indicate high sound power (loud areas). The top left panel of Figure 4 shows a spectrogram of the same clean speech as in Figure 3 but zoomed in on two of the words ("flotte skabe") to better analyse the details. The unique structure of speech elements, or phonemes, composed of vowels and consonants, can be observed in such a spectrogram.

The voiced vowels of the speech are made up of stacks of regularly-spaced harmonics with most power in the low-to-mid frequencies – the parallel quasi-horizontal stripes in Figures 3 and 4, which are produced by vibrations of the vocal folds. The faster the vibrations, the higher the pitch of the voice, which leads to more widely spaced harmonics. How these harmonics vary across time and frequency is important to perceive intonation of the speech. Also look at how the harmonics are not all of equal brightness/power for a given vowel. Some stripes are brighter relative to others because they lie close to the resonant frequencies of our vocal tract (articulators), which are known as "formants". We can alter the formant frequencies by moving various parts of the vocal tract such as lips, jaws, tongue, and soft palate, which produces different vowel sounds (Schnupp et al., 2011). A correct relationship between the vowel harmonics (their brightness in the spectrograms shown in Figures 3 and 4) is thus essential for a listener to understand which vowel was spoken. In the top left panel of Figure 4, look for example at how the /a/ vowel has less power in the mid-frequencies than the /o/ vowel.

In contrast to voiced vowels, the unvoiced consonants of speech contain shorter spikes of energy mostly in the mid-to-high frequency range. The precise timing of these spikes in relation to the silent gaps surrounding them and how much high-frequency content they have are essential for a listener to understand which consonant was spoken. For example, the consonant /s/ is generated by squeezing air through the constricted opening between the tongue and the hard palate, thus producing a highly turbulent flow which causes high-frequency vibration in the air. As seen in the clean speech spectrogram (Figure 4, top left panel), /s/ has power distributed from 3 kHz up to 10 kHz. When there is not enough power in the high-frequency region near 10 kHz, the consonant /s/ will look more like an /f/ and be more easily confused with it.

Let us now have a look at how the different hearing aids preserve such fine speech details. For this purpose, we obtained HATS recordings in a loudspeaker setup with clean speech played from the front at 0° and background speech-shaped noise played from the sides and the back at -112.5°, 112.5°, and 180°, with speech and noise both at 75 dB SPL (0 dB SNR). The top right panel in Figure 4 shows the spectrogram of such a noisy speech when it is not processed by any hearing aid. See how the fine speech details now blend into the noise. The job of the hearing aids is to make these details stand out again.

We then fitted the HATS with Oticon More and each of the two tested competitor hearing aids and obtained recordings in these conditions. As opposed to previous

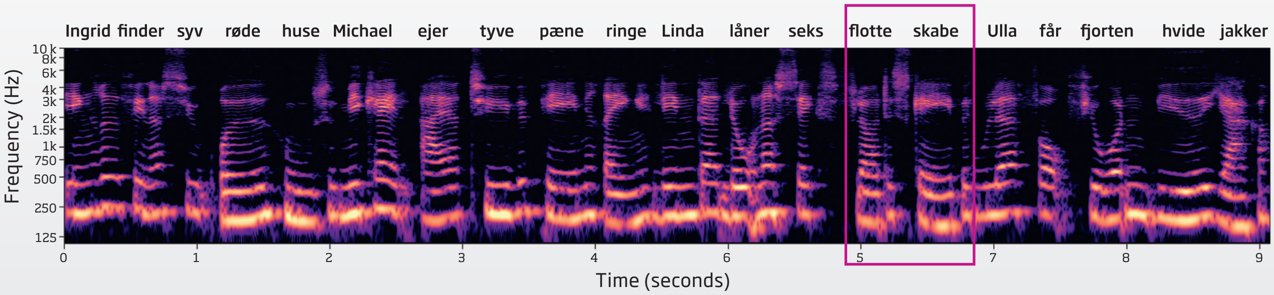

*Figure 3: Spectrogram of clean Dantale II sentences recorded on a HATS without hearing aids. The two words framed in red, "flotte skabe", correspond to the zoomed-in view in Figure 4.*

SNR measurements, for this analysis, all hearing aids were adjusted to the respective manufacturer's default prescribed settings in their fitting software without any further adjustments of settings or features, with the provided gain based on a sloping moderate hearing loss (N3 standard audiogram, Bisgaard et al., 2010) using each manufacturer's proprietary rationale, reflecting what many users would experience by default in such a situation. The three lower panels in Figure 4 shows the spectrograms of the noisy speech at the output of each of the tested hearing aids, obtained once the hearing aids were in their stable state (i.e., after being in the scene for more than 45 seconds).

Compared to the noisy speech spectrogram, all hearing aids create some contrast between the areas with speech energy and the areas dominated by the background noise. However, there are clearly noticeable differences between the spectrograms. If we first focus on the vowel /o/ in "flotte", look at how Oticon More applies precise amplification to make the clear harmonic structure of the vowel stand out. For Competitor A, the harmonic structure is visible but does not stand out as much, while for Competitor B, the harmonic structure itself seems less clear and distorted. The same pattern is observed for the vowel /a/ in "skabe". If we now look at the consonant /s/ in "skabe", we can see that Oticon More is the only device that transmits sound energy all the way up to 10 kHz, creating a larger contrast with other consonants such as /f/ or /t/ than both competitors. Competitor A does generally not provide much gain above 6 kHz, with a risk for the user to miss out on the high-frequency content of consonants. For Competitor B, this high-frequency speech energy has a tendency to blend into the noise.

It is also visible that More provides more sound power outside the speech areas, letting the user access more of the background overall than the two competitor hearing aids. However, because the fine details of speech are well preserved and the contrast between speech and the background remains large, as shown in the above output SNR results, being aware of the background noise does not come at a cost for speech understanding.

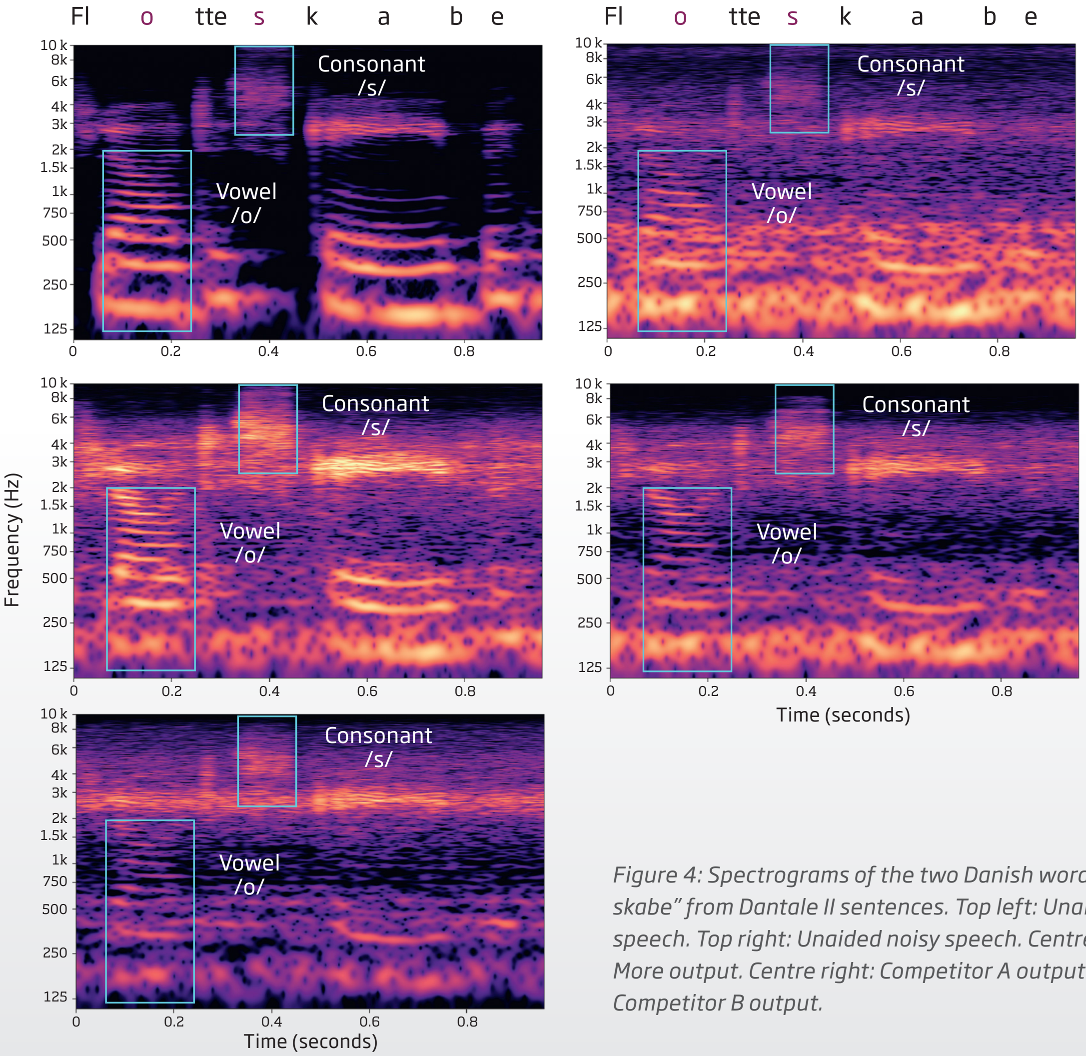

*Figure 4: Spectrograms of the two Danish words "flotte skabe" from Dantale II sentences. Top left: Unaided clean speech. Top right: Unaided noisy speech. Centre left: Oticon More output. Centre right: Competitor A output. Bottom left: Competitor B output.*

In other words, you can hear the noise but it is not disturbing. Another observation is the consistency of the contrast between speech and noise across the whole frequency range with Oticon More, while the strategies of Competitors A and B seem to prioritize noise suppression in the mid-frequency range.

Finally, the amplification strategies of Competitors A and B appear to clearly prioritize specific frequency bands, giving the spectrograms more on/off brightness patterns across frequency. For example, low frequencies are less amplified by Competitor B, in contrast to the frequency area around 3 kHz. As can be seen in the clean speech spectrogram, most of the speech power lies in the low-frequency area. While all hearing aids do provide more gain towards high-frequencies to compensate for the sloping hearing loss, Oticon More better preserves this power balance between the low-frequency vowels and the high-frequency consonants.

Overall, this spectrogram analysis reveals that Oticon More gives the user better access to speech details than the two tested competitor hearing aids. This is due in part to the processing of the DNN that has learned how it should balance speech and the background in such a scene and to its ability to process sound across frequency channels. In addition, the precise amplification of MSA is essential in preserving those finely balanced speech details throughout the whole frequency range when gain is applied.

## Adapting rapidly to new sound scenes

When a hearing aid user enters a new environment, the hearing aids need some time to adapt their automatic features to the new sound scene before they can provide the user with a stable listening experience. During the adaptation period in a complex scene, the hearing aid user may not receive the desired help in terms of SNR improvement straight away, with costs for speech understanding and listening effort. The adaptation period of a hearing aid can vary greatly across models and manufacturers. In order to visualize the adaptation process of Oticon More and the two tested competitor hearing aids, we obtained spectrograms over a longer time period. Figure 5 shows spectrograms for the first 27 seconds of the output recordings obtained with the same speech and noise signals as in the previous section, with Oticon More shown at the top. First note how the More spectrogram is much brighter in the areas corresponding to the detailed structure of speech. Then compare the brightness of the three spectrograms in the mid-frequency area and how it changes as time progresses (most easily seen in the mid-frequency regions between 750 Hz and 1.5 kHz). For all three hearing aids, this area becomes darker over time, indicating a progressive attenuation of the background noise as the hearing aid adapts to the new sound scene. Let us now observe at which point in time the contrast between speech and noise has stabilized, meaning that the remainder of the time, the spectrogram has an unchanging pattern. For the competitor hearing aids, it takes up to more than 20 seconds for the contrast between speech and noise to become visually stable. In contrast, Oticon More reaches a steady state of operation within approximately the first 6 seconds of being in this newly encountered sound scene.

Based on visual inspection of the spectrograms, Oticon More clearly adapts more rapidly to changing sound scenes than the competitors. But can we quantify such a dynamic effect and which consequences it has for speech understanding? One way to do this is to analyse the different hearing aid outputs with a metric that tells us how much of the original speech has been preserved by the processing of the hearing aids. A well-established metric developed for this purpose is the short-time objective intelligibility (STOI, Taal et al., 2011a), which has often been used in research as an objective metric to evaluate the technical performance of hearing aids in terms of speech understanding (e.g., Sanchez Lopez et al, 2018). The STOI metric is a number between 0 and 1 that has been shown to highly correlate with speech understanding in noise in both listeners with normal hearing and with hearing loss (Smeds et al., 2014; Taal et al., 2011b). In order words, the higher the STOI metric is, the better the user can understand speech.

The STOI metric was calculated in 9-second intervals for each of the output recordings corresponding to the spectrograms of Figure 5. The results are shown in Figure 6, with the STOI metric on the left vertical axis. The right vertical axis shows the corresponding predicted speech intelligibility from the logistic STOI mapping function obtained in normal-hearing listeners with the Dantale II speech material mixed with speech-shaped noise (Taal et al., 2011a). Note that the predicted intelligibility should thus be seen as an approximation. A higher STOI metric does nonetheless still indicate higher speech understanding for listeners with hearing loss (Smeds et al., 2014). In addition to Oticon More yielding the highest STOI metric among the three hearing aids, the progression of the STOI metric as a function of time confirms that Oticon More reaches its maximum intelligibility earlier than the two competitors. In fact, performing the same analysis with shorter time intervals shows that the STOI metric with More already reaches a plateau approximately after the first 6 seconds, confirming what we visually observed in the spectrograms. This means that the user does not need to wait a long time to access clear speech information when entering a new sound scene and will be less likely to miss out on conversations when the sound environment changes.

## Conclusion

New technical evidence obtained in realistic sound scenes shows that the new audiological perspective in Oticon More outperforms the traditional directionality, noise reduction, and compression approaches of two of the latest premium competitor hearing aids at several levels:

- More makes the speech stand out more from the background in real complex scenes, helping the user to access speech around them without the need to directly face the talker;
- More gives better access to speech details in the presence of noise, better preserving speech cues that are important to recognize speech elements, leading to higher speech understanding;
- More adapts more rapidly to changing sound scenes, such that users reach high speech understanding more quickly as their environment dynamically changes.

In Part 2 of this competitive benchmark, these technical findings will be put to the test by letting hearing-aid users compare the sound of Oticon More with that of the same two competitor hearing aids.

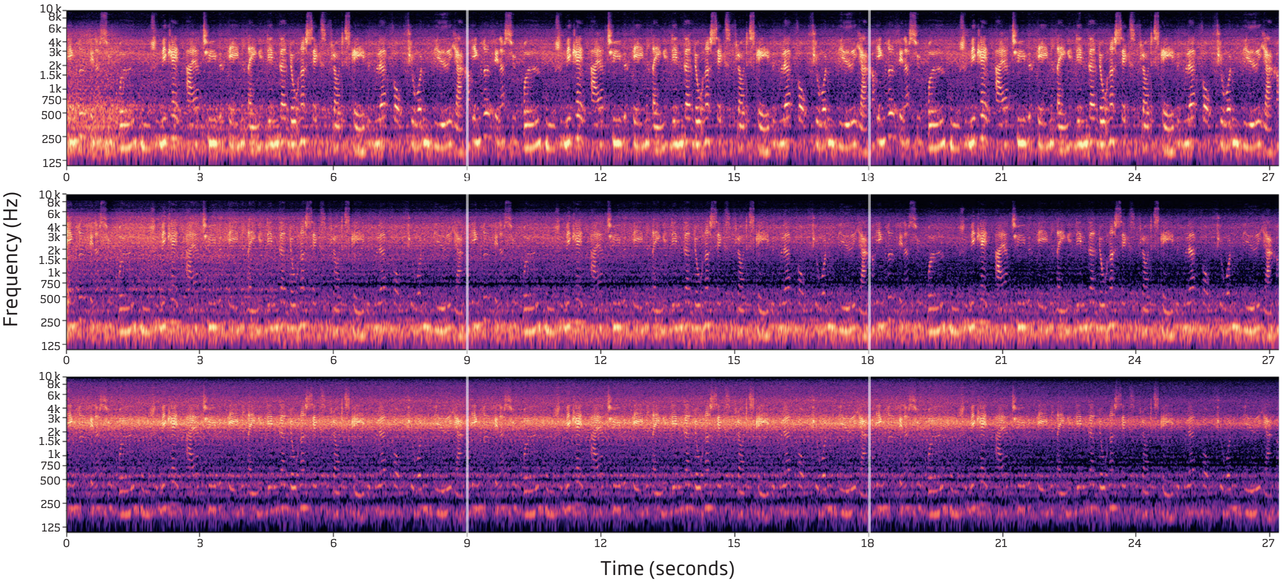

*Figure 5: Spectrograms generated from the first 27 seconds of output recordings of Oticon More (top), Competitor A (middle) and Competitor B (bottom).*

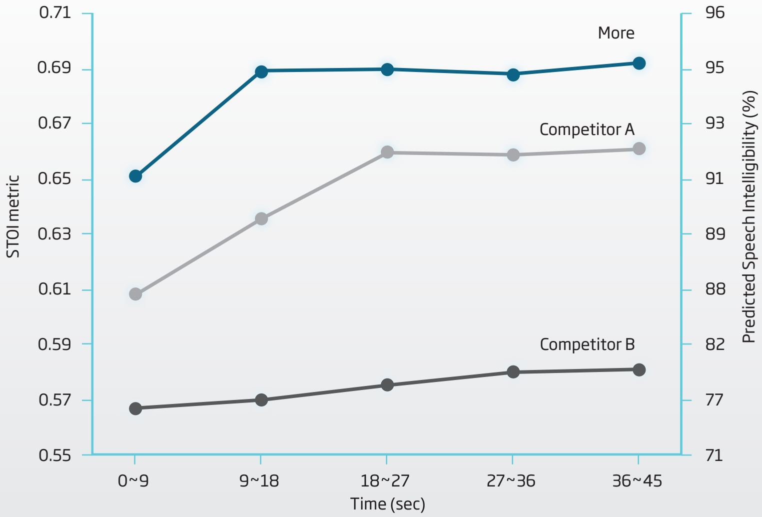

*Figure 6: STOI metric (left y-axis) and corresponding predicted speech intelligibility (right y-axis) as a function of time in 9-second time intervals. Predicted intelligibility is based on the STOI mapping function for normal-hearing listeners with Dantale II sentences in speech-shaped noise.*

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