SoundRecover

Background information from the field of audiology

For people with hearing loss, it is crucial that they can perceive and discriminate high-frequency sounds easily and accurately. There are three main areas where high-frequency sounds are important:

- Speech intelligibility: Many sounds or phonemes that contribute significantly to speech intelligibility include mainly high-frequency components. For example, the phoneme /s/ is used in the English language to identify plurals, so a listener can assess whether there are one or more objects. Depending upon the age and gender of the speaker this phoneme has a spectral peak between 4 and 10 kHz. For men, the energy maximum is usually between 4 and 6 kHz and for women it is often between 7 and 10 kHz. In every language there are many such speech sounds, which can be distinguished only if the high-frequency components of the signal are audible (Simpson et al., 2005). The perception of this high-frequency range is particularly important for children in language acquisition, as it provides the potential to understand language and learn to reproduce it correctly (Stelmachowicz et al., 2002).

- Speech understanding in noise: Speech understanding is particularly difficult when a listener is attempting to understand speech in a noisy environment. The high frequency part of the speech signal is particularly important because, unlike the low frequency part, it is less susceptible to being masked by the relatively intense low-frequency components of many common types of noise. Therefore, it is particularly important in such acoustic environments that the high-frequency phonemes are audible and distinguishable.

- Localization: Moreover, the perception of these high-frequency characteristics gives valuable information for the identification and localization of sound sources (Blauert, 1982). It is important that this high frequency information is available for both ears (Dubno et al., 2002).

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Background information from the field of audiology

Methods to provide more amplification to the important high frequencies

For listeners with a high-frequency hearing loss, adequate amplification is needed to provide audibility of high-frequency speech sounds. Two methods used are extending the bandwidth beyond 8 kHz and frequency lowering:

- ### Extension of bandwidth

  The traditional method would be to extend the bandwidth of the hearing device and apply high frequency amplification at those frequencies necessary to perceive and distinguish high frequency phonemes. However, apart from the problem of dead regions at high frequencies which cannot be solved with just high-frequency amplification, there are a couple of other issues to be considered:

  - The necessary amplification required to extend the bandwidth requires even more amplification than with the frequency compression technique especially at the high frequencies. As the sensitivity of the receiver decreases at frequencies higher than 5 kHz (fig 1), this increase in amplification requires a drastic increase of the amplitude in this high frequency area. Consequently, the output stage will become saturated, which in turn generates artifacts that cannot be digitally eliminated.

  - Amplification is highest in the frequency region where the residual dynamic range is smallest. As recruitment in this area is much higher it requires a large amount of amplitude compression which results in diminished sound quality.

  - Generally, high frequencies are perceived by hearing aid users to be more unpleasant than lower frequencies. This can lead to an unpleasant perception of even soft levels of high frequencies. Tones are reportedly perceived more as a buzz rather than a pure tone, (Moore & Tan, 2003) especially in those frequency areas where the hearing loss is highest.

  - The risk of feedback increases. A feedback suppression can partly support, but this results in higher power consumption and possibly generation of artifacts.
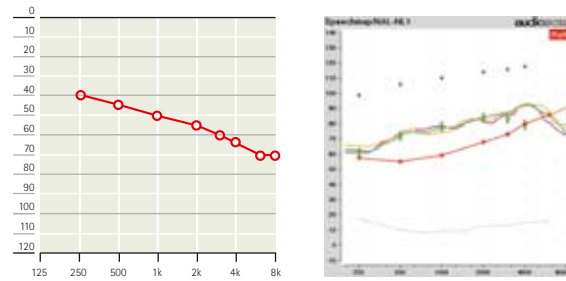

Figure 1
The left shows a moderate hearing loss. The right diagram shows the target gain of three hearing aids with moderate power using Audioscan Verifit. All hearings aids claim to have extended bandwidth up to 10 kHz but can only provide enough gain up to 6 kHz. From 6 kHz and above these same hearing aids begin to decrease in high frequencies gain and the required gain cannot be achieved by any hearing aid, even power models. As this is measured in the coupler, the result would be even worse if it was measured using real ear measurements. This shows that the extended bandwidth cannot be achieved at the ear drum.

- ### Frequency lowering

  This sound processing technique shifts the high-frequency information to a lower-frequency region so it can be more easily accessed by the listener's residual hearing. Studies suggest that these frequency lowering technologies may benefit adults and children with high frequency hearing loss and that this benefit varies across individuals (Simpson, 2005). One such approach is the Phonak proprietary non-linear frequency-compression, SoundRecover. By compressing the output bandwidth of the signal by a specified ratio, SoundRecover effectively extends the perceptual bandwidth and improves audibility and discrimination of high frequency signal components. This is demonstrated in figure 2. In general, frequency compression splits the incoming hearing aid signal into two channels, determined by the cut-off frequency.
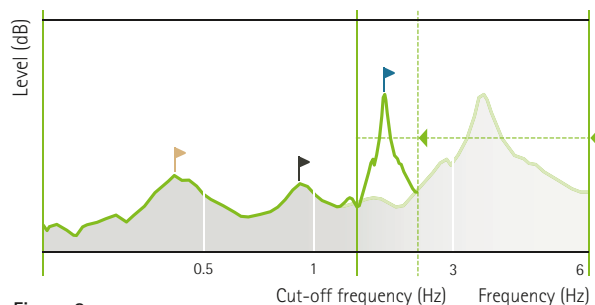

Figure 2
The SoundRecover algorithm moves the sounds to an adjacent area with better hearing, where they can be processed and amplified, without interfering with the audibility of lower frequency sounds.

Background information from the field of audiology

The low frequency channel is not subjected to any frequency compression (keeping the harmonic structure in this frequency area to better distinguish between male and female voices) whereas the high frequency channel is compressed into a narrower bandwidth. This results in sound being lowered in frequency within the high-frequency channel (Simpson et al, 2005). Research suggests that non-linear frequency compression provides speech perception benefits for adults and children with high frequency hearing loss by providing access to new high-frequency cues although presented at lower frequencies (Bohnert et al, 2010; Glista et al, 2009; Glista et al, 2009; Simpson et al., 2005; Simpson et al, 2006; Wolfe et al., 2010, Wolfe et al 2012).

Due to the amplification problems that extending the bandwidth creates, Phonak decided to use the frequency compression algorithm, SoundRecover, in all their hearing aids, which can effectively solve the problems that extended bandwidth cannot.

Benefits for the hearing aid user

SoundRecover has proven many benefits such as:
- Increased detection, discrimination and recognition of sounds.
- Significant improvement in intonation and overall voice quality.
- Improved speech intelligibility in quiet and in noise.
- Improved detection of high-pitched sounds and better speech understanding (most noticeable when listening to high-pitched talkers such as women and children, softly spoken people, or high-frequency sounds such as /s/ or /f/).
- All audiometric configurations can benefit from SoundRecover.

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Technical description

The objective of SoundRecover is to restore the audibility for high frequency inputs up to approximately 10 kHz. This unique approach is designed to compress the signal above a specified and adjustable cut-off frequency. The amount of compression applied to this frequency band is specified by the compression ratio. All frequencies below the defined cut off frequency starting point remain unchanged, preserving the quality of sounds delivered to the hearing aid user.

Frequencies which are further away from the cut-off frequency (higher frequency direction) are shifted to a greater extent to lower frequencies than a frequency which is closer to the cut off frequency. For example, for a given compression setting, the maximum energy of a female /s/ (usually around 9 kHz) will be shifted further towards the cut-off frequency than the maximum energy of a male /s/ (5 kHz) although the correct frequency order is still maintained.

The compression works without any delay, therefore there are no time constants required or artifacts heard. Figure 3 shows the response curve of the frequency transmission of a non-linear frequency compression. The cut-off frequency in this example is at 1758 Hz and the compression ratio at 2.9:1.

Thus it is possible to calculate the maximal input frequency $f_{IN,\,max}$ which depends on the sampling rate of the maximal output frequency $f_{OUT,\,max}$ using the following formula:

$$f_{OUT,\,max} = f_{IN,\,max}^{\frac{1}{CR}} \cdot f_{Cutoff}^{1-\frac{1}{CR}}$$

The current realization of SoundRecover in all Phonak hearing aids allows for an individual setting of the cut-off frequency dependent on the hearing loss between 1.5 kHz and 6 kHz. The compression ratio is automatically adjusted to a value between 1.5:1 and 4:1 according to the selected cut-off frequency.
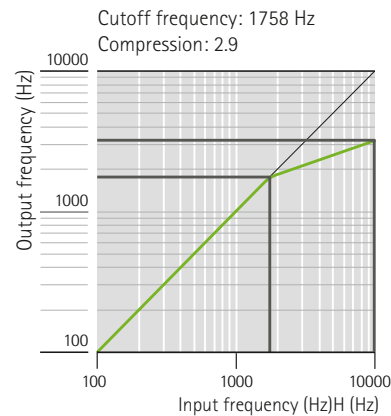
Cutoff frequency: 1758 Hz
Compression: 2.9

Figure 3
The response curve of nonlinear frequency compression, SoundRecover, for a cut-off frequency of 1758 Hz with a compression ratio of 2.9.

Technical description

The cut-off frequency and compression ratio values are combined within Phonak fitting software to define one SoundRecover setting which clinicians are able to adjust, in order to fine tune the settings. It is dependent on the hearing loss of the end user, setting the value of SoundRecover to the setting of the better hearing loss in both devices. This also helps to avoid left and right confusions for perception.

The SoundRecover setting can be adjusted to strengthen or weaken how SoundRecover affects sounds. The lower the cut-off frequency and higher the compression ratio, the stronger SoundRecover affects the sounds. To weaken how SoundRecover settings, a higher cut-off frequency and a lower compression ratio should be set.

In all Phonak hearing aids, the input bandwidth of frequency compression is 10 kHz. This means that the highest frequencies the hearing aid senses is 10 kHz. All acoustic information up to 10 kHz is processed and put to the output signal regardless of how strong or weak SoundRecover is set. The frequency to which maximum input frequency (10 kHz) is mapped to is called "upper edge frequency". Above the upper edge frequency the hearing aid does not provide sound. The upper edge frequency can be easily seen in the Phonak Target curve displays which show gain curves or output level curves. By looking at the upper edge frequency, we can see which frequency 10 kHz is mapped to and determining how much usable audibility is available with conventional amplification. Phonak Target pre-calculation takes care of that and in case of doubt sets the upper edge frequency conservatively, i.e. errs to higher frequencies. With the cut-off frequency and the compression ratio given the upper edge frequency is determined.

Clinical evidence

SoundRecover is the most researched frequency lowering approach in the hearing industry. Multiple studies in the past few years have confirmed that with SoundRecover, speech intelligibility is often improved both in quiet and in noise, for all ages, degrees of hearing loss and audiometric configurations including asymmetric configurations.

Speech intelligibility
Nyffeler (2008b) showed evidence of improved speech intelligibility with SoundRecover activated. Eleven adults with moderately-severe to profound, sensorineural hearing loss (SNHL), who were fitted with SoundRecover showed improvement of speech intelligibility over time, in both quiet and noisy situations. Users were assessed at baseline with their own hearing aids and then wore the Phonak Naída hearing aids with SoundRecover activated for at least two months. Their hearing performance was evaluated using objective and subjective tests at five assessment sessions during the study period. The Oldenburger Satztest (OLSA) was used to evaluate speech intelligibility in noise, using Phonak Naída hearing aids with SoundRecover versus the subject's own hearing aids. Patient-reported outcomes were assessed by questionnaire.

After two months of use, tests indicated that SoundRecover not only prevented acoustic feedback and discomfort resulting from excessive loudness, due to high levels of high-frequency amplification, but also improved speech intelligibility versus the user's own hearing aids. Subjective evaluations showed that SoundRecover significantly improved user satisfaction of the hearing device and improved perceived sound quality, after two months of use. The study concluded that SoundRecover significantly improved the listening experience in quiet and noisy situations, as well as increased the pleasantness of environmental sounds and subject's own voice, resulting in a highly satisfactory overall impression.

Evidence for speech intelligibility in children shows that SoundRecover "On" provides better detection and recognition of high-frequency sounds than wideband amplification for children with mild hearing loss (Wolfe and John, 2012). A double-blinded study of 11 children with mild sensorineural hearing loss hearing loss were fitted with Phonak

Nios H2O and Oticon Safari 300 BTEs using DSL v 5.0 target for children. The Phonak hearing aids had SoundRecover "On" and "Off" while the Oticon Safari 300 used wideband amplification. The children were tested after four weeks of use with each setting. The final conclusion of the study showed that the children had better threshold and recognition for the phonemes /s/ and/sh/ with SoundRecover "On" compared to only having wideband amplification.

Speech understanding in noise
Bohnert et al (2010) compared the SoundRecover algorithm to conventional amplification hearing aids, using both a test of speech understanding in noise (Oldenburger Satztest-OLSA) and subjective questionnaires. In this study, 11 experienced hearing aid users with a severe to profound sensorineural hearing loss were tested. Seven subjects showed enhanced levels of understanding in noise (OLSA) using SoundRecover. "However, four out of the eleven subjects showed no enhanced levels of understanding in noise using SoundRecover". Evaluation using questionnaires, demonstrated an increased level of satisfaction after two months of wearing the experimental devices with SoundRecover ($p = 0.08$) and after four months of wearing ($p = 0.09$), respectively, compared to conventional hearing aids.

Asymmetric audiometric configurations
John et al, (2013), demonstrated the benefits (improved audibility and speech perception in quiet; significant improvements in word recognition) of SoundRecover with asymmetric sloping sensorineural hearing loss (SNHL). The study also assessed the difference in benefit when the SoundRecover cut-off frequency and compression ratio are programmed symmetrically based on the better-ear status according to the manufacturer's defaults, versus separate calculations for each ear. In the study, 28 adults with asymmetric sloping SNHL were recruited. All of the adults were experienced hearing aid wearers but did not use any frequency lowering technology.

The conclusions drawn from the study showed that adults with asymmetric sloping SNHL demonstrated improvements in the recognition of high-frequency speech phonemes in quiet, as well as improvements

Clinical evidence

in speech understanding in quiet and in sound quality. A trend was observed toward better speech recognition in noise with use of SoundRecover, but it was not significant. There was also no performance difference observed, in regards to SoundRecover set to the better ear thresholds versus the thresholds of each separate ea. This finding confirms how to fit asymmetric hearing loss with SoundRecover.

Music perception

Uys et al (2012) demonstrated evidence of improvements in music perception when using Nonlinear Frequency Compression (SoundRecover). This study investigated the potential for improvement in music enjoyment, as a result of the expanded audibility of high frequency sounds. The performance of hearing aids with SoundRecover was evaluated in comparison to conventional amplification, using the Music Perception Test (MPT) and a subjective questionnaire. Forty experienced hearing aid users with a moderate to severe sensorineural hearing loss participated in the study. Results showed that the use of SoundRecover significantly improved subject's perception of timbre and melody (fig. 4).

Beside their participation in the music perception test, the subjects also completed a questionnaire to gauge subjective perception of musical sound quality. Most subjects reported more satisfying sound quality with SoundRecover for all the musical qualities assessed namely overall fidelity, tininess and reverberance but not for loudness, as depicted in figure 5. No subjects reported worse sound quality and musical enjoyment with SoundRecover compared to conventional amplification.
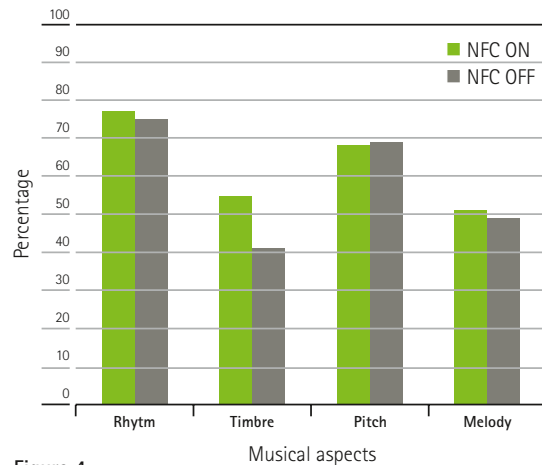

Figure 4
Subjects' mean scores for the rhythm, timbre, pitch and melody sections of the Music Perception Test with SoundRecover off and SoundRecover on
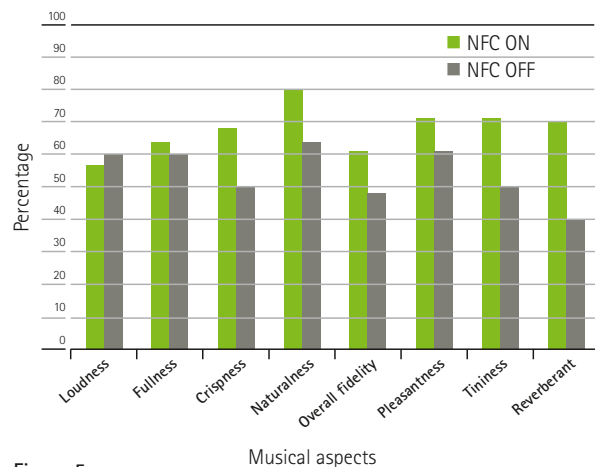

Figure 5
Subjects' mean scores for the different musical qualities assessed in the questionnaire with SoundRecover Off and SoundRecover on

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Fitting and fine tuning SoundRecover

The Phonak Target fitting software pre-calculates a setting of the cut-off frequency and the compression ratio parameters using the audiogram of the better hearing ear. The hearing care professional can further fine tune these settings – either with a macro-parameter which manages both cut-off frequency and compression ratio in an audiologically effective manner or by tuning both parameters separately (SoundRecover extended tool in Phonak Target 3.1 and higher). In the current implementation of SoundRecover, cut-off frequencies are selectable between 1.5 and 6 kHz. The compression ratio is between 1.5:1 and 4:1. The pre-calculation is always set the same for both ears based on the better hearing ear. The fitter however can fine tune both sides independently.

In most fine tuning cases, the one slider is suited to fine tune SoundRecover. The split parameters are helpful if in an individual case, there is a strong trade-off between familiarity of sounds and discriminability of compressed sounds. Both cut-off frequency and compression ratio affect audibility of compressed sounds. Changing cut-off frequency affects more strongly the familiarity of sound quality and changing compression ratio affects more strongly the discriminability of compressed sounds.

Adjusting both parameters also affect the upper edge frequency. For a person with normal hearing, there is sufficient audibility of high-frequency sounds as well as the familarity of everyday life sounds. There is no problem with distinguishing sounds from each other. For a person with moderate hearing loss we need to change sounds (amplification, frequency lowering) in order to restore audibility. Changing sounds is always accompanied by some degree of initial unfamiliarity. If managed properly, the hearing impaired person can acclimatize to it and have full benefit from it. Also SoundRecover induces some unfamiliarity, e.g. to tonal sounds and to compressed /s/ sounds – the stronger SoundRecover is set. Another auditory aspect also needs to be considered: ability to discriminate of compressed sounds. The higher the compression ratio is, the more similar the compressed sounds are – as they get spectrally nearer to each other. As with other hearing aid settings (e.g. amplification) there is an individual optimum for SoundRecover settings.
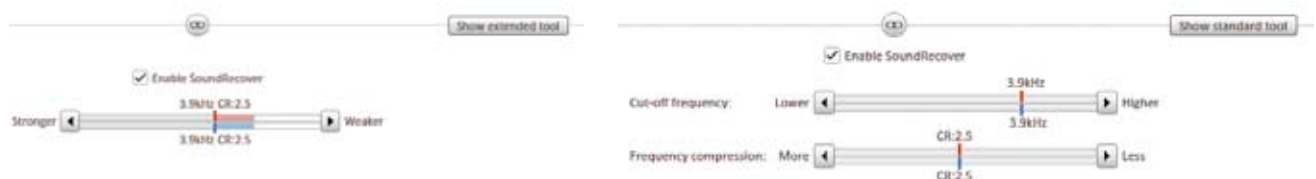

Figure 6
The SoundRecover tool in Phonak Target 3.1. The image on the left shows the SoundRecover standard tool that adjusts the cut-off frequency and the compression ratio together. The image on the right is the SoundRecover extended tool that allows the hearing care professional to adjust the cut-off frequency and the compression ratio independently. All sliders (on the left and on the right) affect the upper edge frequency.

Fitting and fine tuning SoundRecover

There are four auditory/perceptual goods that depend on SoundRecover parameters:

- Audibility of high-frequency sounds increases by reducing cut-off frequency and increasing compression ratio.
- Discriminability of high-frequency sounds increases by reducing compression ratio
- Familiarity of high frequency sounds (e.g. /s/ does not sound lisping) increases by increasing cut-off frequency, to a lesser degree also by reducing compression ratio. It also increases by acclimatization.
- Familiarity of voiced speech sounds and tones increases by increasing cut-off frequency, to a lesser degree also by reducing compression ratio. It also increases by acclimatization.

Figure 7 shows the perceptual goods depending on SoundRecover parameters schematically. The green spot in the middle symbolizes a well-balanced setting of SoundRecover. The gray areas show parameter configurations which all have one or many drawbacks. On the right side the green spot is not the same for all hearing impaired people. It is individual. Phonak Target pre-calculation covers many of this individuality. But in some individual cases, fine tuning SoundRecover really can make a difference.

The following gives you hints how to address hearing issues which may be related to SoundRecover settings:

High frequency sounds, e.g. /s/, are not sufficiently audible:
If high frequency audibility cannot be reached by adjusting the hearing aid's gain and MPO, the fitter can lower the cut-off frequency if it is not already rather low (below 2.5 kHz). The trade-off to this is that the familiarity of high frequency sounds can be affected.
Another suggestion is to increase the compression ratio. An exception to this is with severe to profound losses: Discriminability of /s/ and /sh/ could become insufficient.

Poor discriminability of high frequency sounds, e.g. /s/ and /sh/:
Decrease the compression ratio and lower the cut-off frequency slightly in order keep audiblity of high frequency sounds stable.

Low familiarity of high frequency sounds, e.g. /s/ sounds lisping or familiarity of harmonic sounds, e.g. vowels, voiced consonants, tones:
Increase the cut-off frequency but the trade-off to this is that it can affect the audibility of high frequency sounds.

Figure 7
A qualitative scheme of SoundRecover parameters affecting perceptual goods: Audibility, discriminability, familiarity of sounds.

It is important to check that the SoundRecover settings are well-balanced (audibility, discriminability, familiarity) in both an adult and pediatric fitting. Phonak has the following suggestions.

1. To check that high frequency audibility is sufficient
   Adults:
   - Speak at challenging voice level /s s s s/, /sh sh sh sh/; check if sounds are heard
   - Use /s/ and /sh/ examples of Audibility Fine Tuning in Target (suitable for moderate to severe losses)
   - Do free-field narrowband audiometry; check if aided thresholds are sufficiently low
   - Phoneme Perception Test – Measure detection thresholds and check if they are in target range
   Children
   - Below 12 months: DSL verification – check in SPLoGram if /s/ and /sh/ are above threshold
   - Above 12 months, additionally: check if child speaks s and sh at all

2. To check if high frequency discriminability is sufficient
   Adults:
   - Speak at challenging voice level /s sh s sh s sh/; check if sounds can be distinguished
   - Use /s sh s sh/ sound in Audibility Fine Tuning in Target (suitable for moderate to severe losses)
   - Phoneme Perception Test – Measure distinction performance, see if it is sufficient
   Children
   - Below 12 months: DSL verification – Check in SPLoGram if /s/ and /sh/ are not completely overlapping
   - Above 12 months, additionally: Check if child speaks /s/ and /sh/ differently

3. To check that high frequency familiarity is sufficient
   Adults
   - If familiarity of high frequency sounds is an issue, the customer will immediately tell you because speech contains lots of /s/
   - Speak /mississippi/, ask if /s/ are ok or lisping
   - Let customer speak /mississippi/, ask if /s/ are ok or lisping
   Children
   - Early years: As children only learn to verbally communicate there are no familiarity issues at these ages. Stick to DSL presetting and electroacoustic verification of frequency compression settings.
   - Later years: Check as with adults

4. To check if the familiarity of harmonic sounds is sufficient:
   Adults
   - If familiarity of harmonic sounds is an issue the customer will immediately tell you because speech contains lots of them
   - Speak to the customer, words with voiced sounds only, e.g. /ama/, /mom/, /alabama/ etc, ask if words are ok or strange
   Children
   - Early years: As children only learn to verbally communicate there are no familiarity issues at these ages. Stick to DSL presetting and electroacoustic verification of frequency compression settings.
   - Later years: Check as with adults

Verification of SoundRecover using the Phoneme Perception Test

Verification of hearing aid fittings using currently available speech tests does not give a good indication of which hearing aid parameters should/could be changed (gain, frequency-lowering algorithms, sound cleaning, etc.) in order to optimize audibility and speech recognition for the hearing-impaired person. The Phoneme Perception Test aims to assess a client's hearing abilities to detect, distinguish and recognize high frequency phonemes such as /s/ and /sh/. The results provide an indication as to whether additional adjustments are required to maximize the benefit of the hearing aids, such as activating SoundRecover or strengthening or weakening SoundRecover. The results of the test also function as a supporting mechanism to restore the clients audibility for high-frequency fricative sounds (/s/, /sh/).

The Phoneme Perception Test has scientifically been shown to be highly specific and sensitive to high frequency audibility and hearing issues related to that – reduced recognition, reduced distinction. It has been shown that the test is highly sensitive to variations of high frequency gain and to types and degrees of frequency lowering. So the test is well-suited as an assessment tool for working at high frequency restoration in clinical practice.

Tips and tricks

1. It is important to verify that the SoundRecover setting by ensuring and that the high frequency sounds, /s/ and /sh/, are audible and distinguishable.

2. A period of 2-4 weeks of acclimatization is recommended to get used to SoundRecover.

3. If the fitter wants to switch SoundRecover off permanently, it is possible to do so in Phonak Target setup > Fitting > Fitting defaults

   Fitting defaults
   ☐ SoundRecover off per default
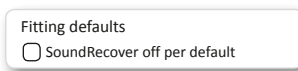
4. The familiarity, audibility and discriminability of speech sounds as a basis of speech intelligibility and hearing comfort can be adjusted by moving the cut-off frequency and compression ratio sliders within the SoundRecover extended tool.

5. The Phoneme Perception Test is a useful tool to verify the SoundRecover settings.

6. The Audibility Fine Tuning tool can also be used to fine tune SoundRecover. With this tool the important phoneme can be acoustically presented and the relevant parameters can be changed easily.