IMPROVING HIGH FREQUENCY AUDIBILITY WITH SOUND SHAPER

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Abstract

Speech communication contains much redundant information which helps us to understand. Hearing loss takes away some of the acoustic redundancy of speech, typically in the high frequencies. Limitations with today's hearing aids can mean that it may not be possible to restore these cues. Frequency lowering is an alternative strategy for improving high frequency audibility. ReSound introduces Sound Shaper, a frequency compression algorithm that can improve high frequency audibility with minimal effects on sound quality.

INTRODUCTION

Speech is essential in human social interaction. The many different environmental conditions in which we communicate impose considerable demands on the speech process. For example, the acoustic speech signal can be significantly altered by noise or other interfering signals as it travels from speaker to listener. To assist us in understanding, speech communication is linguistically and acoustically redundant. By this it is meant that the speech contains more information than is needed to decode it. Linguistic redundancy is easy to demonstrate in written language. Few competent readers of English would have trouble understanding the following sentence, even though all the vowels are replaced with "x": Xt xs nxt hxrd tx rxxd thxs sxntxncx."

An analogous example in the acoustic domain is vowel formant transitions, which indicate place of articulation for the consonants that precede and follow them, thereby providing an additional acoustic cue to help identify those consonants correctly. Phonological knowledge of the language being spoken helps narrow the possibilities further. In addition, grammatical, semantic and pragmatic knowledge influence the listener's ability to use the context of a fragmented message to understand the message[1].

The relative importance of different types of redundancy in speech and communication shifts depending on both acoustic and intrinsic factors. This is illustrated by the band importance functions for different types of speech material in calculating the Speech Intelligibility Index[2] as shown in Figure 1. When the speech material consists of nonsense syllables, the importance of high frequency acoustic information for correct identification (red curve) is more important than when continuous discourse is used (black curve) and knowledge of the language can help in correct identification. This has important implications for children who are in the process of learning language, as they cannot take advantage of linguistic redundancy and pragmatics to the degree that adults can. It has been shown that children require better signal-to-noise ratios than adults to identify words and sentences at the same level of performance[3,4]. Thus children are likely to rely even more on acoustic redundancy in speech than adults. One effect of hearing loss is that it strips away some of the acoustic redundancy in speech, as it reduces audibility for speech sounds. This adds to ambiguity for all hearing impaired listeners but may be most devastating for children's speech recognition and language-learning.
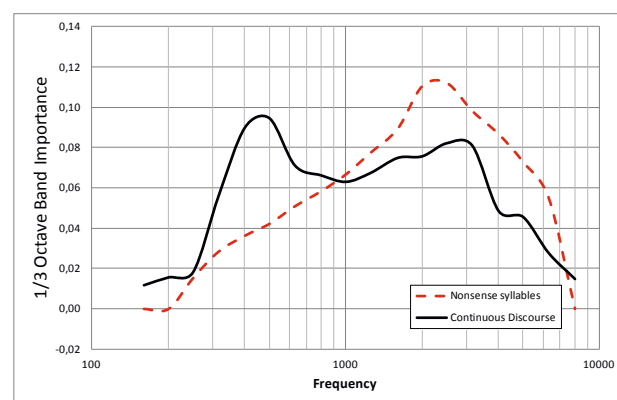

Figure 1: One-third octave band importance functions for Nonsense Syllables and Continuous Discourse.

Amplification helps restore some acoustic redundancy to the signal that is available to the hearing impaired listener. A primary goal of fitting amplification to hearing impaired children is to provide access to as much speech information as possible. However, the common sloping configuration of hearing loss makes it particularly challenging to provide audibility for high-frequency fricatives such as /s/, /sh/, and /f/. The /s/ sound in English as well as some other languages is a grammatical marker that is important to speech understanding. Even for adults with post-lingual hearing loss who require less acoustic redundancy in the signal, conventional amplification may limit adequate access to high frequency speech information or environmental high frequency sounds.

Although restricted high frequency bandwidth of the hearing instrument can be a reason for insufficient amplification to cover the speech frequencies, today's hearing instruments are more likely to be limited by acoustic feedback or by the response of the receiver. For example, individuals with severe-to-profound hearing losses are fit with powerful devices. The receivers in high power hearing instruments have larger diaphragms with a greater mass, and thus a lower resonance. This means the response rolls off in the higher frequencies to a greater extent than hearing instruments for less severe hearing losses.

In addition to technical limitations with amplification, it has been suggested that providing high frequency amplification may not always be beneficial. The presence of a non-functional cochlear "dead region" with few or no functioning inner hair cells may not transduce energy from the basilar membrane, leading to off-frequency listening and possibly worse speech understanding[5].

Apart from high amplification, another tool for improving audibility of high frequency sounds is frequency lowering. This term refers to sound processing strategies that move information from higher frequency areas to lower frequency areas, where audibility is better. The idea behind frequency lowering is that audibility of these sounds even at "misplaced" frequencies is more beneficial than no audibility at all. The most used frequency lowering strategy is frequency compression. Similar to the well-understood amplitude compression used in hearing instruments for decades, frequency compression changes the relationship between the input and output of the hearing aid above a certain cut-off, or kneepoint, frequency. ReSound introduces frequency compression in hearing instruments with Sound Shaper.

UNDERSTANDING SOUND SHAPER

Conceptually, Sound Shaper frequency compression can be understood as similar to the spacing of keys on a piano keyboard. The upper panel of Figure 2 shows a normal keyboard and the lower panel shows a representation of an "unrolled" cochlea. The basal end of the cochlea (right) is most sensitive to high frequencies and has broader frequency tuning, as shown by the superimposed auditory filters. Sound Shaper "squashes" the frequencies above a cut-off frequency so that they are closer together. This is illustrated by the narrower spacing of the keys on the keyboard in Figure 3. In this way more information is conveyed into a region that is audible for the hearing instrument wearer.
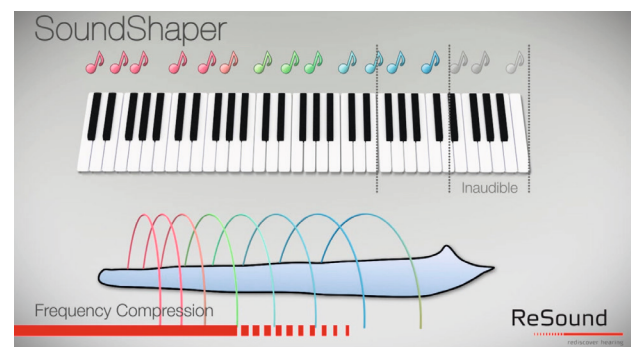

Figure 2. High frequency sounds may be inaudible depending on the hearing loss and limitations of the hearing instrument.
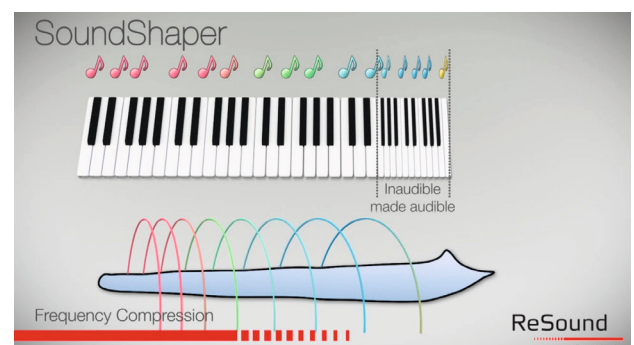

Figure 3. Sound Shaper compresses high frequency information, moving it to a region that is more likely to be audible.

SOUND SHAPER IN DETAIL

Similar to amplitude compression, Sound Shaper can be described with the help of an input/output function.

An example of this is shown in Figure 4. Instead of input and output levels, input and output frequencies are plotted. The darker blue part of the curve is the frequency region in which Sound Shaper is not active. The frequency relationships here are not changed by Sound Shaper. The lighter blue part of the curve is where Sound Shaper is active, and demonstrates how the input frequency corresponds to a lower output frequency. The point between the darker and lighter blue parts of the curve is the cut-off frequency, also called the frequency compression kneepoint. Sound Shaper only affects frequencies above the cut-off frequency. The relationship between the input frequency and the output frequency in the light blue part of the curve is called the frequency compression ratio.
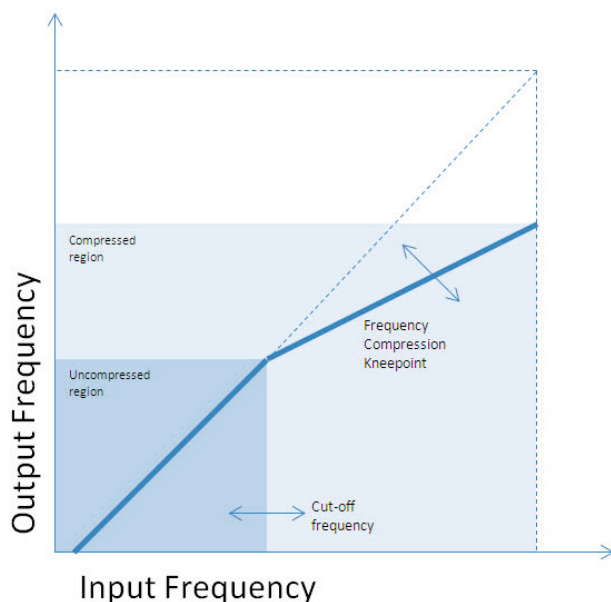

Figure 4: Relation between input and output frequencies. Frequency compression is applied to the high frequencies (light blue) above the frequency compression knee point, while the lower frequency region (dark blue) is left uncompressed.

COMPARISON TO OTHER APPROACHES

The literature on the benefit of frequency compression is consistent only in its inconsistent findings. While it is clear that some individuals benefit from this type of technology, it is equally clear that some don't. Furthermore, there is as yet no surefire way to identify those who will benefit. It is also uncertain how frequency compression affects sound quality. While normal hearing listeners are highly sensitive to the effects of frequency compression, hearing impaired listeners may find a range of frequency compression settings indis-

tinguishable from the unprocessed sound in terms of sound quality[6]. Generally speaking, there is evidence that both normal hearing and hearing impaired listeners prefer no frequency compression or moderate frequency compression settings to strong frequency compression settings for music[7]. With this in mind, Sound Shaper was developed to provide the minimum effect to do the job and to have the least distorting effect on the signal. This has implications for the available settings, as well as the method used to compress the sound.

Sound Shaper processing creates a proportional relationship between the input and output frequencies. This is in contrast to other frequency compression algorithms that create a non-proportional relationship. The difference in these two approaches on the signal is illustrated in Figure 5. Each of these graphs shows input frequency on the x-axis and output frequency on the y-axis. The intensity is indicated by color, with red being most intense, and blue being least intense. For these measurements, a 90 dB SPL pure tone was swept through a range of frequencies. The swept pure tone processed with ReSound Warp amplitude compression for a mild-to-moderate hearing loss is shown in the top left. The top right panel shows the output with Sound Shaper activated. The cut-off frequency is obvious, and the frequency compression is also clearly illustrated by the reduced slope of the input/output function. Note that there is relatively little energy present in the output above the cut-off frequency that was not also in the input.

The bottom left panel of Figure 5 shows the swept pure tone processed by another manufacturer's hearing instrument with amplitude compression as prescribed for a mild-to-moderate hearing loss. The bottom right panel shows the output with this device's frequency compression algorithm activated. It was set to have a similar cut-off frequency and compression ratio as the measurement done with Sound Shaper. The other manufacturer's frequency compression processing creates a non-proportional relationship between the input and output frequencies. This generates more distortion products above the cut-off frequency, as shown by the "fuzziness" of the curve in the frequency compressed region.
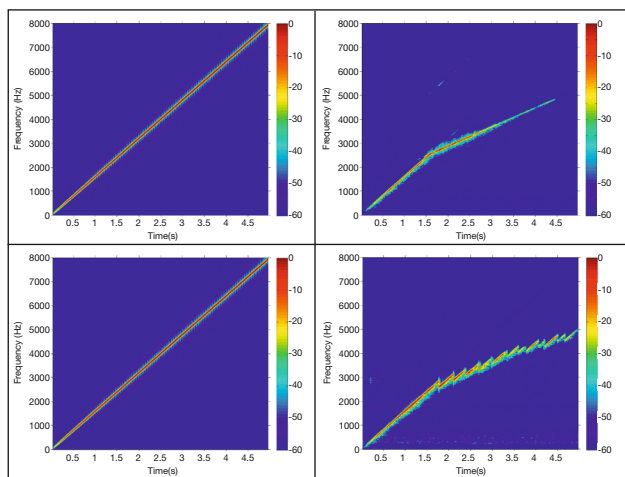
Figure 5: Frequency input/output functions for a swept pure tone were measured without (left) and with (right) frequency compression activated. The top panel shows the results for Sound Shaper and the bottom panel for another manufacturer. The proportional frequency compression strategy used in Sound Shaper results in much less distortion above the cut-off frequency.

To further investigate how these different approaches to frequency compression might affect sound quality, 10-second segments of pop music presented at 60 dB SPL were also recorded through each hearing instrument programmed for a mild, moderate and sloping hearing loss, and the results were analyzed for predictive sound quality judgments through the Hearing Aid Speech Quality Index (HASQI)[8]. The HASQI is based on the "coherence" between the input sound and the output of the hearing aid. The coherence provides a physical measure of the added noise and distortion relative to the original signal. The HASQI has been found to correlate well with subjective quality judgments by normal-hearing and mild-to-moderately hearing impaired listeners. For the experiment, gains were set according to the default prescription for the particular audiogram, and recordings were made without frequency compression, and with two frequency compression settings which were similar between the two devices. These are referred to as "moderate" and "strong". The "moderate" setting had a cut-off frequency as close to 3 kHz as possible and a compression ratio as close to 2:1 as possible. The "strong" setting had the same compression ratio but a cut-off frequency as close to 2 kHz as possible. The recordings were processed off-line to determine the HASQI score. For both frequency compression algorithms, predicted sound quality was reduced as the aggressiveness of the processing was increased. However, the effect was more pronounced for the algorithm us-

ing a non-proportional approach, while Sound Shaper maintained a relatively better result (Figure 6). Results for all three types of hearing losses showed the same trends; for simplicity, the average of these results for each frequency compression setting are depicted in the figure.
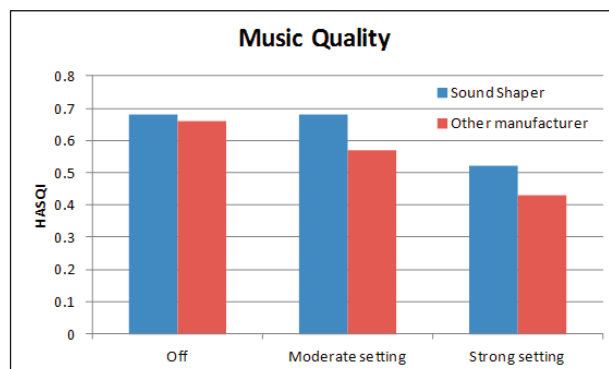

Figure 6: HASQI predictions of sound quality for music showed that Sound Shaper preserves sound quality relatively better than a non-proportional frequency compression method.

APPLYING SOUND SHAPER

By its very nature, frequency compression alters the spectral relationships of the sound relative to the original signal. The most obvious manifestation of this is that the output spectrum of the frequency compressed sound has a smaller bandwidth than the original. While the result of this type of processing may improve audibility for some high frequency sounds, the changes may also have disruptive perceptual effects. Given the lack of clear direction on who is a candidate, how to appropriately fit the technology, and what results to expect, a conservative approach to applying frequency compression is prudent.

In developing Sound Shaper, one objective was to define settings that could provide benefit, but which would preserve sound quality to the extent possible. A second goal was to simplify fitting.

Initial lab investigations showed that cut-off frequency has a much greater effect than compression ratio. Therefore, only two compression ratios were selected for further evaluation. Eight combinations of cut-off frequencies and compression ratios were subsequently tested with 17 hearing impaired participants with steeply sloping high frequency hearing losses and 20 participants with severe-to-profound hearing losses.

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Table 1 presents the setting combinations.

Setting ID	Cut-off [Hz]	CR
"Off"	n/a	n/a
1 (weakest)	5000	1.33
2	4000	1.33
3	4000	2
4	3500	2
5	3000	2
6	2500	2
7	2250	2
8 (strongest)	2000	2

Table 1. Eight combinations of cut-off frequencies and compression ratios were evaluated in-house with hearing impaired listeners.

For 20 of the participants, the field trial setting was chosen based on a real ear measurement protocol to optimize audible bandwidth. For the remainder of the participants, the field trial setting was selected based on which setting yielded the best performance on the UWO Plurals test[9]. For multiple participants, scores were equal for more than one setting. In these cases, the most conservative setting with the highest cut-off frequency was selected. In addition, real ear insertion gain measurements were conducted on 40 ears with the Ling sounds /s/ and /sh/ to document the effect of all 8 setting combinations compared to "Off". It was observed that the measurements clustered in 3 distinct groups (Figures 7 and 8).

Outcome measures included clarity ratings, sound quality ratings of male voice, female voices and music, speech testing, and the Speech, Spatial and Qualities of Hearing Scale (SSQ)[10]. Similar to other studies with frequency compression, group data did not suggest optimum settings or average benefit. However, individuals showed improvement on outcome measures individually, and indicated individual preferences for this type of processing. Individual differences in scores for Sound Shaper on and off on the UWO Plurals test seen in Figure 9 illustrate the variability. Those who preferred Sound Shaper processing reported that the sound was crisper and clearer than with conventional amplification.
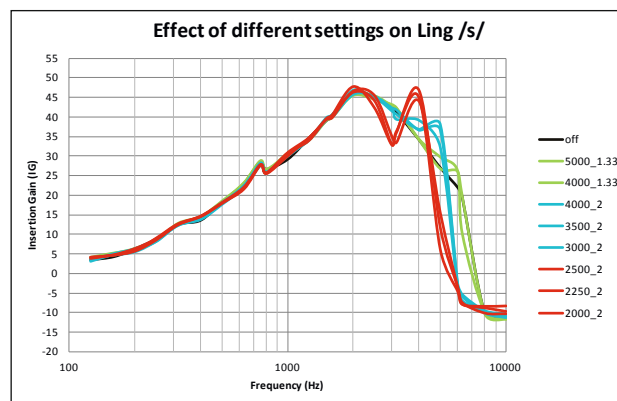

Figure 7. Real ear measurements with the Ling /s/ stimulus clustered into three very similar groups.
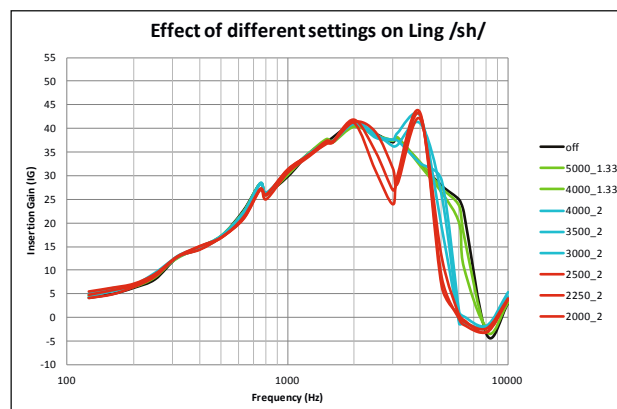

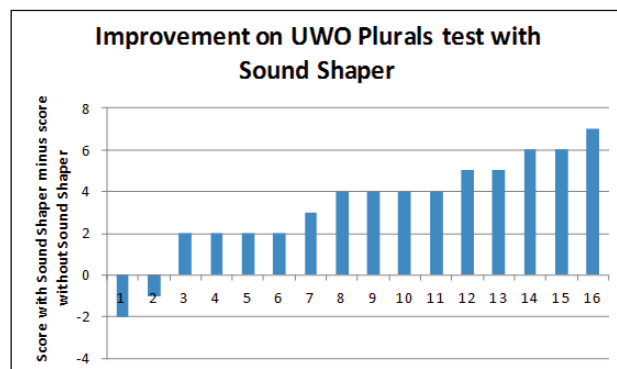Figure 8. Real ear measurements with the Ling /sh/ stimulus clustered into three very similar groups.

Figure 9: Most individuals showed improvement on the UWO Plurals test with Sound Shaper activated, which indicates that better audibility for high frequency speech sounds was achieved.

FITTING SOUND SHAPER

In the Aventa fitting software the Frequency lowering feature is defaulted to "off" in each hearing instrument based program. Because of the groupings of effects of the tested settings in the real ear measurements, and the fact that there often was not one particular

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setting that yielded the most benefit for individuals, a straightforward approach for fitting Sound Shaper was chosen. Thus there are 3 Sound Shaper settings corresponding to the groupings observed in the real ear measurements. The Sound Shaper setting options in Advanced Features include "Off," "Mild," "Moderate" and "Strong" (Figure 10). The settings correspond to the cut-off frequencies and compression ratios in Table 2.
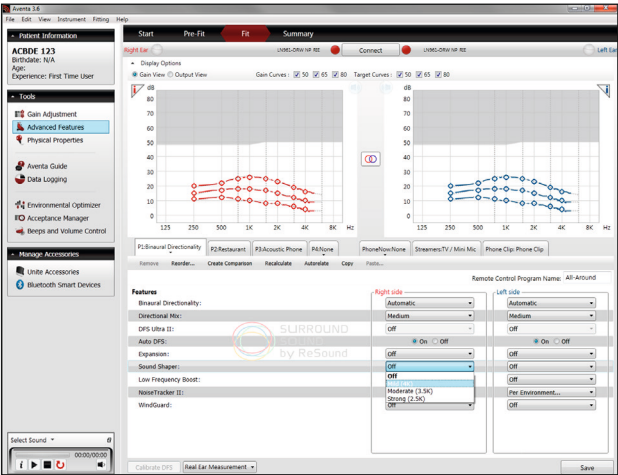

Figure 10. Sound Shaper settings are found in the Advanced Features screen.

Sound Shaper setting	Cut-off frequency and Compression Ratio
Mild	4000Hz, CR 1.33:1
Moderate	3500Hz, CR 2.0:1
Strong	2500Hz, CR 2.0:1

Table 2.
Sound Shaper settings in Aventa and the corresponding cut-off frequencies and compression ratios.

When the drop-down menu for Sound Shaper is clicked, the recommended setting for the individual audiogram will be indicated in bold typeface. In cases where conventional amplification is expected to provide good audibility for a wide bandwidth, the recommended setting will be "Off". The criteria for recommending "Mild", "Moderate" and "Strong" settings as starting points are as follows:

- If the audiogram has a slope of 10dB or greater per octave and the slope begins at 4000Hz or higher, a "Mild" setting is recommended.
- If the audiogram has a slope of 10dB or greater and the slope begins at 2000Hz, a "Moderate" setting is

recommended (Figure 11).
- If the audiogram has a slope of 10dB or greater and the slope ends at 2000Hz, a "Strong" setting is recommended (Figure 12).
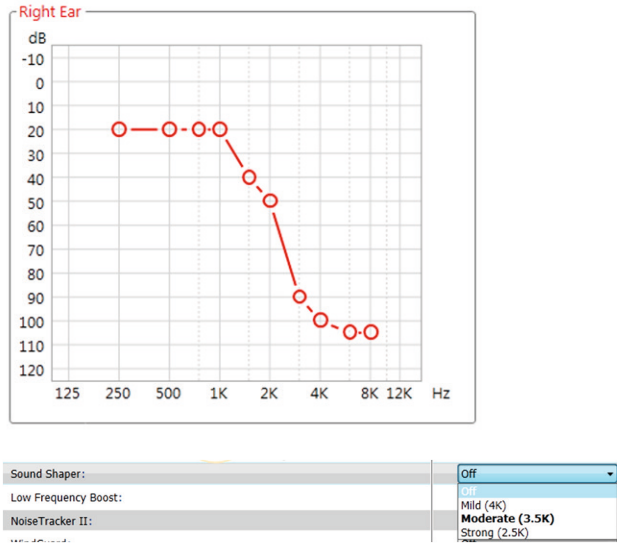

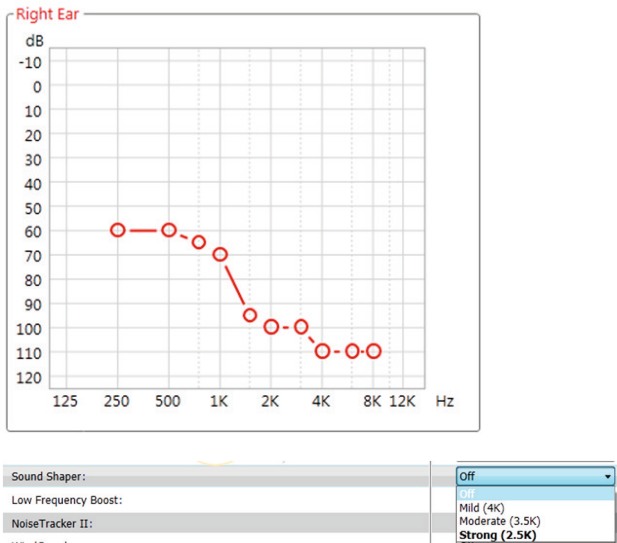Figure 11. Example of a recommendation for the "Moderate" Sound Shaper setting.

Figure 12. Example of a recommendation for the "Strong" Sound Shaper setting.

When Sound Shaper is activated a grey area in the gain graph will appear indicating the cut-off frequency and the frequency range that is compressed (Figure 13).
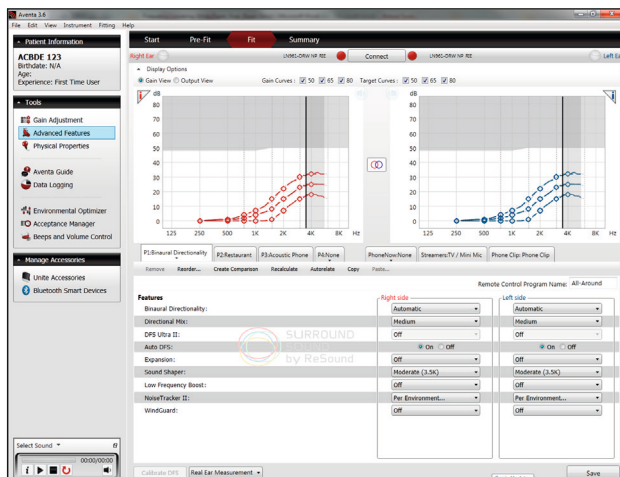
Figure 13. The solid dark vertical line indicates the cut-off frequency when Sound Shaper is turned on, while the grey shaded area shows the region of frequency compression.

Sound Shaper is enabled per program and per ear.

Figure 15. Aurical FreeFit display showing verification measurements of the Ling /s/ (purple) / Ling /sh/ (blue) stimuli with Sound Shaper on "Strong".

VERIFICATION OF SOUND SHAPER

Routine clinical verification of gain and output at the eardrum level or in a coupler represents best practice with any hearing aid fitting to ensure that appropriate gain is provided. Fitting hearing aids with frequency lowering is no different in this regard. Real ear measurement equipment manufacturers have begun to include special tests and/or stimuli to help the hearing care professional verify that frequency lowering algorithms are providing added audibility for high frequency sounds. Examples of these are shown in Figures 14 and 15. Specific protocols have been developed[11, 12].
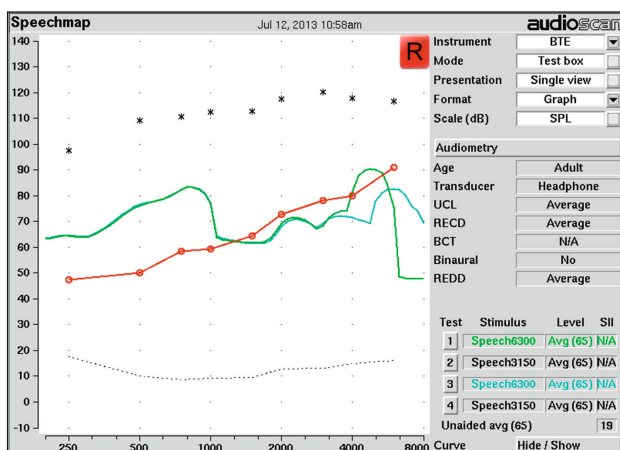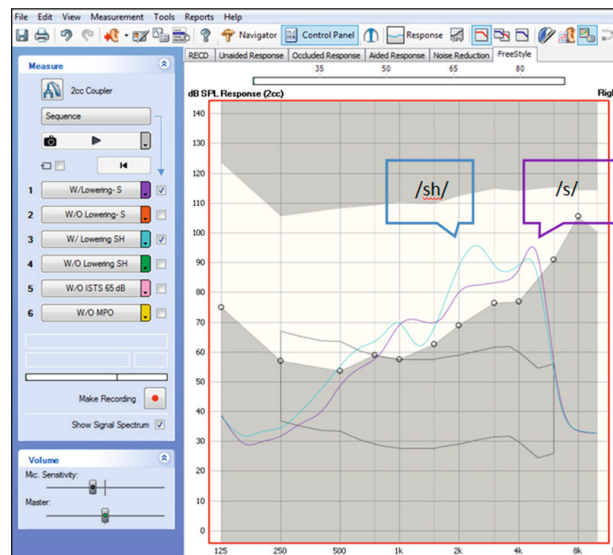

Figure 14: Audioscan Verifit display showing a verification measurement with Sound Shaper "off" (blue) and Sound Shaper on "Moderate" (green).

SUMMARY

Sound Shaper offers clinicians an alternative tool to help improve high frequency audibility for users when hearing instrument limitations prevent conventional amplification from doing an adequate job. This tool may be especially significant for fitting pediatric clients, who likely rely to an even greater extent on the acoustic redundancy of speech than post-lingually hearing impaired users. Sound Shaper has been shown to improve audibility of high frequency speech sounds, like /s/, without detrimental impact on sound quality. Finally, fitting Sound Shaper is simple – the combinations of compression ratio and cut-off frequency settings have been optimized to reduce complexity for clinicians.

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