

INDEPENDENT STUDY IDENTIFIES SURROUND SOUND BY RESOUND AS TOP-RATED

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Abstract

Excellent sound quality and technology firsts are common claims made by hearing instrument manufacturers. However, these claims have been difficult to document in an impartial manner. This paper presents results of a study on sound quality in high-end hearing instruments which used a unique methodology designed to eliminate bias in the participants' judgments. The results support that the Surround Sound by Resound™ signal processing strategy provides superior sound quality to hearing instrument users. The Resound LiNX™ hearing instrument incorporates Surround Sound by ReSound processing, and extends sound quality to include direct stereo sound streaming from Apple iPhone®, iPad® and iPod touch®. This is a technology first, as ReSound LiNX is the first "Made for iPhone" hearing instrument that can connect wirelessly with no intermediate device required.

INTRODUCTION

Did you ever try an unfamiliar dish while on a holiday and find that it tastes so good that you seek it out at home, only to be disappointed that it isn't as good as you remember? This common experience isn't due to faulty memory, but rather to the impact of multiple stimuli on a sensory experience. Even hearing has an effect. For example, it has been shown that seafood tastes better when you hear ocean sounds while eating it, even if you are not anywhere near a real ocean.¹

Sound is inarguably a powerful aspect of human life. Not only is verbal language communication dependent on producing and receiving sound, we rely on sound to convey the nuances and subtleties of emotion, to orient ourselves and navigate in our environment, and for enjoyment and entertainment. The quality of the sound we hear is an essential part of the human experience. It follows that sound quality must also be an essential consideration in hearing instruments. The sound delivered by the hearing instrument shapes how the user experiences their world. In light of this, research showing that aspects of sound quality such as clarity and naturalness of sound are highly correlated with satisfaction with hearing instruments is not surprising.²

Despite its importance, sound quality can be difficult to define for the hearing instrument wearer. This is because hearing instrument processing strategies significantly change the incoming sounds as they aim to compensate for lost auditory function.

For example, the prescriptive fitting formulae we typically use to adjust the frequency response of hearing instruments will always result in a weighting of gain in certain frequency regions, thereby negating the idea of an acoustic signal which is an exact reproduction of the original. For hearing instrument wearers, it may be more appropriate to think of sound quality as describing how amplified sounds fit within their range of hearing, whether sounds are distorted, and the degree to which undesired sounds such as background noises, acoustic feedback or signal processing artifacts are heard and found annoying. This is consistent with the way in which various dimensions of hearing instrument satisfaction in the MarkeTrak surveys are grouped as relating to sound quality, including not only "better sound quality", but also "less whistling and buzzing", "more soft sounds audible", and "loud sounds less painful".

Recognizing the importance of sound quality, ReSound applies a sound processing strategy that provides wearers with exceptional speech understanding, enhanced awareness of their sound environments, and rich, vibrant, fully detailed sound quality. Surround Sound by ReSound incorporates advanced technologies that model, clean, balance and stabilize the digitalized signal before it enters the hearing instrument receiver. ReSound LiNX not only embodies this strategy, but extends it to the world of consumer electronics as the first hearing instrument to offer direct connection with Apple's iPhone, iPad and iPod touch for phone calls and high quality stereo, sound streaming. This paper reviews some of the



ReSound LiNX allows users to stream high quality stereo sound directly from iPhone, iPad and iPod touch.

elements that strongly contribute to sound quality, and presents evidence that the combination of Surround Sound by ReSound technologies results in perceived sound quality that exceeds that of most other hearing aids.

MEASURING SOUND QUALITY

Virtually all hearing instrument manufacturers claim excellent sound quality in their products. Such claims easily go unchallenged due to the lack of methods for impartially assessing sound quality in hearing instruments. For one thing, sound quality is perceptual. While some objective measurements of physical properties, such as distortion, may correlate to some extent with sound quality judgments, they do not tell the whole story. To complicate matters further, varying dimensions of sound quality, such as “brightness” or “naturalness”, may be weighted differently in importance among individuals. Finally, auditory memory limitations make it difficult for hearing instrument wearers to fairly assess the fine details between different hearing instruments.

In an effort to quantify the sound quality benefits of the Surround Sound by ReSound strategy, ReSound partnered with an external laboratory* to capture sound quality judgments of experienced hearing instrument users for various current advanced technology hearing instruments. The methodology, described in detail elsewhere³, differed from other sound quality assessments in two important ways. First, the eighteen moderately hearing impaired participants were able to make unlimited, direct comparisons of stimuli that were recorded through each of the test hearing instruments and presented to them under headphones. Not only did this mitigate auditory memory limitations, it also prevented the participants from knowing anything about the specific hearing instruments or making any judgments based on other characteristics, such as brand, appearance or fit of the devices. Secondly, participants used

sliders on a visual continuous scale to rank the test hearing instruments in terms of preference, from “like most” to “like least”. This forced them to use the entire scale, which can provide better discrimination among stimuli than if multiple samples can be rated the same. Another unique characteristic of this evaluation was that it made use of trained assessors who had qualified for participation via performance on various discrimination tests⁴ to complete the evaluation.

Seven sound scenarios were presented and evaluated. The red data points in Figure 1 show the overall preferences, which represent the averaged ratings across all eighteen assessors and sound scenarios. The black data points present results from an earlier study using the same methodology and the previous high-end products from various manufacturers for comparison. ReSound products were consistently top-rated for sound quality over two generations of hearing instruments.

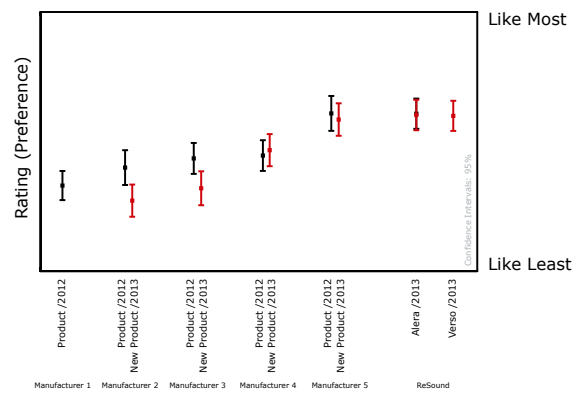


Figure 1. ReSound hearing instruments are top rated in sound quality across product generations thanks to Surround Sound by ReSound technologies that carry through all ReSound products.

FOCUS ON A NATURAL HEARING EXPERIENCE

Why is ReSound technology preferred for sound quality? First, the ReSound philosophy of sound processing respects natural hearing processes. Because hearing is a job done by the brain, development efforts are focused on emulating the ear to deliver the best possible signals to the brain. For most people who are hearing instrument candidates, the challenge is to transmit sound via a damaged sensory end-organ, the cochlea, to an intact auditory processing system in the brain. It follows that hearing instruments should attempt to provide “healthy ear” functions to the impaired ear. Sound is delivered to the sophisticated, intricately functioning auditory processing systems of hearing

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instrument wearers. The device fit to each ear delivers a separate and different signal to the brain, which the auditory cortex processes to form one fused auditory image. This image is what is heard.

Second, modern hearing instruments apply other processing designed to enhance the listening experience by reducing side effects of wearing them, such as feedback and amplification of undesired sounds. While the Surround Sound by ReSound signal processing strategy includes technologies that emulate the healthy ear, such as the Warp compression system, and support binaural hearing, such as Binaural Directionality™, it also uses technologies that add to the enjoyment of wearing hearing instruments. These include technologies such as NoiseTracker™ II noise reduction and DFS Ultra™ II for elimination of feedback. It is important that these types of features function in a transparent manner in order to provide the best sound quality. In other words, they should accomplish specific goals without the listener noticing them. While it may seem counterintuitive that sound processing features should not call attention to themselves, this strategy provides the most natural listening experience.

ReSound also ensures that the sound quality is part of the entire listener experience, including streamed sounds. This includes wireless connections to streaming of audio signals from ReSound Unite™ accessories using proprietary 2.4 GHz radio frequency technology. And with ReSound LiNX, high quality stereo sound can also be streamed directly from an iPhone, iPad and iPod touch using Apple audio streaming technology.

WARP: THE FOUNDATION OF SOUND QUALITY

The main function of hearing instruments is to amplify sounds. Thus, the compression system is the most important aspect of any sound processing. If the compression system doesn't "get it right" for the hearing instrument wearer, it doesn't matter how good other sound processing may be. As a pioneer in hearing loss compensation, ReSound was the first to introduce Wide Dynamic Range Compression in hearing instruments and has been the only manufacturer to base amplification on an accurate model of cochlear frequency analysis through frequency warping. While most digital frequency techniques for

frequency analysis yield constant bandwidth with uniform spacing of the bands, the ReSound system efficiently resolves frequencies into 17 smoothly overlapping frequency bands corresponding to the auditory Bark scale⁵. The Bark scale incorporates the human auditory system critical bandwidth as the scale unit⁶. With low processing delay and nearly immeasurable distortion, this system provides the foundation of the Surround Sound by ReSound superior sound quality.

Since its beginnings, the ReSound compression system has sought to compensate for the disrupted compressive nonlinear behavior that results from cochlear damage. To achieve this, a compression scheme that resembles cochlear compression with low compression thresholds, compression ratios between 1:1 and 3:1, and fast syllabic-rate attack and release times have been used^{7,8}. The theory behind this compression rationale is that speech intelligibility will improve, because more of the speech signal is made audible. However, a wide body of research on compression in hearing instruments (see Kates⁹ for a review) has not reached a consensus on the optimum compression parameters to fit a given hearing loss. Some researchers have argued for the use of slow compression that emulates linear amplification, with the rationale that compression such as employed by ReSound may result in reduced spectral and temporal contrasts in the signal¹⁰. Generally speaking, fast-acting compression is considered to maximize speech audibility, whereas slow-acting compression is considered to better preserve the acoustic integrity of the original signal and thus, sound quality.

As has been demonstrated earlier in this paper, ReSound hearing instruments are top-rated in terms of sound quality. How is this possible in light of the fast-acting compression scheme, a rationale which may not be considered optimum for sound quality? As ReSound advanced with the WARP compression system, one important development was the introduction of adaptive time constants. Using smart monitoring of input level fluctuations, the WARP compressor is able to apply time constants that adapt to the environmental sound. This strikes a balance between preserving audibility in speech environments and optimizing sound quality in

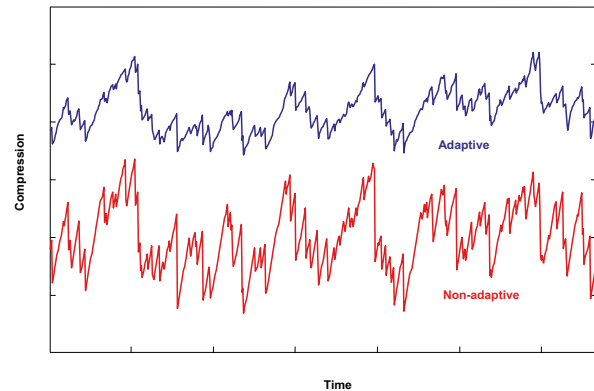
environments with less fluctuating sound levels.

The sounds entering a hearing instrument are rapidly changing in terms of their frequency content and levels, with speech sounds changing over a matter of milliseconds. The time-varying gain of a fast-acting WDRC system is designed to keep up with these variations. However, these gain fluctuations can be the cause of undesirable audible effects under some listening conditions, such as when the input sound consists of a fairly steady noise. Generally speaking, the faster the gain varies over time, the greater the probability that audible artifacts will be produced. One solution to this would be to use longer time constants. If either the attack times or the release times are long, then the compressor calculates an average of the background noise level before reacting to it. This results in more slowly changing gains, and the modulation effects are negligible. However, this slow action would inhibit the system's ability to quickly reduce the gain for sudden increases in the input sound level, or to quickly increase gain for sudden decreases. The result could be annoyance of impulse noises as well as reduced audibility of soft speech sounds.

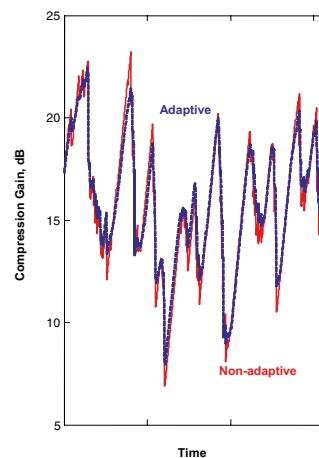
The WARP compressor solution to this dilemma is through the use of adaptive time constants. This slows the reactions to the fluctuations in slowly changing sound environments while allowing rapid response to the important changes in the level of the speech. This proprietary ReSound approach adapts the system's attack times in response to the behavior of the input sound¹¹. Small fluctuations in the sound cause the system to have slow attack times, thereby reducing the gain fluctuations and the resultant distortion. Large increases in the sound level result in faster attack times, thus guaranteeing a quick reaction to sudden significant changes in sound levels.

Measurements of the adaptive compression system show that it is effective. Figure 2 shows the compressor gain in one band over a short period of time for the WARP compressor with adaptive and non-adaptive time constants with white noise as the input. Both have syllabic time constants, with 5 ms attack times and 70 ms release times. The range of gain fluctuation for the adaptive system is about half as great as for the non-adaptive Figure 3 shows the

compressor gain for a speech input with adaptive and non-adaptive time constants. The responses are nearly identical; these results demonstrate how the adaptive system maintains a given time-varying



behavior for speech, while reducing the likelihood of distracting gain variations in response to sounds with



smaller level of fluctuations.

Figure 2. When the input sound is a steady white noise, the compressor gain for the adaptive system fluctuates less over time and provides a smoother response than the non-adaptive system.

Figure 3. When the input sound is speech, the WARP compressor gain for both the adaptive and non-adaptive systems are nearly identical.

ENHANCING SOUND QUALITY WITH DIGITAL NOISE REDUCTION

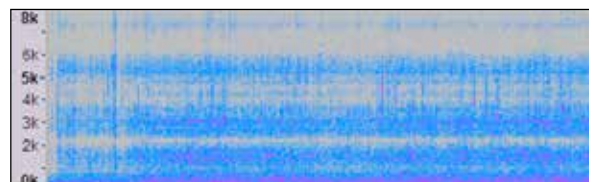
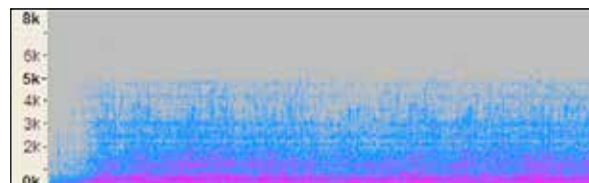
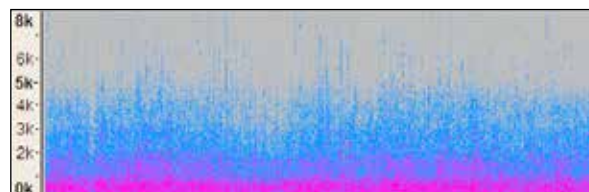
Apart from the WARP compression system, one of the most significant contributing technologies to the superior sound quality proven with ReSound hearing instruments is NoiseTracker II and the environmental dependency of the settings via Environmental Optimizer™ II. Benefits of noise reduction include ease of listening and listening comfort¹², better sound quality¹³, and reduced cognitive load¹⁴. Within the

ever-broadening body of research on noise reduction in hearing instruments, some disagreement in findings is observed. This is to be expected, since noise reduction algorithms can differ quite markedly. The effects of different commercially available noise reduction systems in response to different types of signals were shown to be astoundingly variable in a comparison study by Bentler¹⁵, and yet many hearing care professionals consider noise reduction systems to be equivalent across manufacturers. More recently, the varying acoustic effects of different systems have been confirmed, and subjective measures have also revealed that these differences lead to perceptual differences, at least in normal-hearing listeners¹⁶. Although, it was found that noise reduction systems could reduce noise annoyance and preserve speech naturalness, the degree to which this was achieved with the systems tested differed. Assuming that their results can be extrapolated to hearing impaired listeners, these results have important implications for product selection. The effect of the specific noise reduction system should be a consideration in hearing instrument fitting.

The NoiseTracker II system uses spectral subtraction¹⁷, one of the most widely used methods for enhancement of speech in noise in audio applications. The concept of spectral subtraction is to subtract the short-term noise spectrum from the total signal, leaving only the speech portion. The success of this strategy depends on being able to identify speech and to precisely characterize noise. An additional challenge is to keep up with the dynamic speech and noise make-up of real listening environments. Finally, it is important for hearing instrument users that not all noise be removed from the signal, and that the noise characteristics be preserved. If all ambient noise were removed or if the spectrum of the noise background was altered, this would create an unnatural-sounding experience. Background sounds do need to be audible to the degree that users can recognize and orient themselves in their listening environments. Ultimately, the goal is undistorted speech at the prescribed gain, and undistorted noise at lower level.

The accuracy of NoiseTracker II in reducing background noise was tested by recording speech in a crowd noise background at a 0 dB SNR. This environment is very challenging for a noise reduction

system. Figure 4 shows the spectrogram of the background noise by itself. Time is on the horizontal axis, and frequency is on the vertical axis. The most intense levels appear pink, while the less intense levels are blue. It is clear from Figure 4 that the background noise has the most energy in the low frequencies, but also considerable energy in the mid frequency range. Figure 5 shows the difference between NoiseTracker II off and at the “Considerable” setting. If the spectral subtraction noise reduction system can accurately follow, estimate and subtract the noise spectrum, Figure 4 and Figure 5 should look similar, which in fact they do. This is in contrast to a noise reduction system set to a moderate level in another manufacturer’s high-end hearing instrument, which is shown in Figure 6. The pattern of reduction does not resemble the background noise spectrogram very closely. Not only is little reduction applied where there is most energy in the background noise, but discrete bands of identifiable reduction appear in the



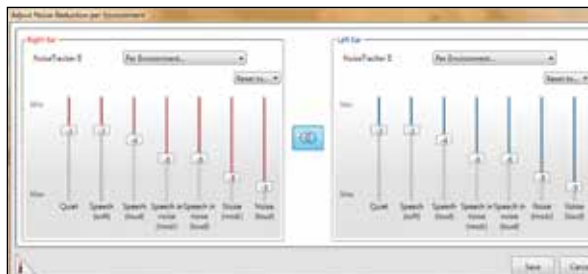
spectrogram. Although both systems may result in less annoyance of the background noise, the NoiseTracker II system is likely to preserve a more natural sounding outcome.

Figure 4. Spectrogram of the background noise only.

Figure 5. Spectrogram showing the difference between NoiseTracker II off and on. The reduction corresponds well to the background noise spectrogram in Figure 4.

Figure 6. Spectrogram showing the difference between another manufacturer’s noise reduction system off and on under the same test conditions. The reduction has a different pattern than the spectrogram of the background noise.

In the example shown in Figure 5, the listening environment consisted of speech in a background of many talkers. While this represents a typical listening situation for hearing instrument users, it is of course not the only one. Many different types of acoustic environments are encountered during the course of a day. An aggressive noise reduction setting can make the sound unnatural in quiet environments. Conversely, a mild noise reduction setting will be less effective at reducing annoyance of background noise in louder environments. The Environmental Optimizer™ II allows for seamless changes to hearing aid function to adapt to these many listening situations. Although situation dependent preferences for both volume and noise reduction have been demonstrated,^{18,19} clinical experience with environmentally dependent changes in hearing instrument settings indicates that wearers prefer changes in hearing instrument settings to be small and gradual for acoustically similar environments. For example, the acoustical environment during a dinner at home with friends may shift from low level speech to speech-in-noise and even to noise with the ebb and flow of conversation and laughter. In this situation, large, quick changes in hearing instrument settings could be perceived as drastic and distracting to the wearer. The advanced classification system



that steers the Environmental Optimizer II settings uses seven categories that are defined in terms of presence and levels of speech and noise to classify acoustic environments.

Figure 7. Optimized levels of NoiseTracker II are prescribed per environment type and can be further personalized in the Aventa3 fitting software.

However, in the many cases where the environment does not clearly fall into one category or when the environment rapidly changes, an algorithm steers the volume and NoiseTracker II settings to a continuously changing combination of the prescribed settings for the three most probable categories. Because of the hearing aid's continuous ability to access combinations

of classifications, gradual behind the scenes changes to the hearing instrument function allow for the wearer to experience transparent sound transitions, which is crucial for natural sound quality.

ENSURING TRANSPARENCY WITH DIRECTIONAL MIX

Although directionality in hearing aids is a well-established way of improving signal-to-noise ratio for users, it does not come without drawbacks. For one thing, directional microphones are less sensitive to low frequencies, causing a roll-off in the response that reduces audibility for sounds in this region. Boosting low frequency gain provides a way of restoring low frequency audibility, but comes with the undesired effect of amplifying the noise floor to the point where it may be audible and objectionable to the wearer. Directional microphones may also distort near-field signals, such as wind blowing across the microphone or the user's own voice. Phase distortions between bilaterally fit hearing aids with directionality can disrupt interaural time differences, and behind the ear microphone placement causes a loss of spectral cues, thereby complicating localization of sound. All of these factors can negatively impact sound quality, especially when directional processing is embedded in other processing schemes that change microphone mode depending on the acoustic environment.

To circumvent sound quality issues with conventional, full-band directionality, ReSound uses Directional Mix, a bandsplit directional processing algorithm in which incoming signals are processed based on their frequency content. High frequencies are processed as a directional response, while low frequencies are processed as an omni directional response. The lack of sound quality differences between directional and omni directional responses allows for transparent microphone mode switching as well as applying asymmetric directional fitting strategies. Groth et al²⁰ found that bandsplit directionality was preferred to full band directionality in terms of sound quality, and was indistinguishable from an omni directional response. This result was confirmed by Moeller & Jespersen²¹, who reported that listeners were unable to distinguish sound quality differences among the different Directional Mix settings. An additional advantage of bandsplit directionality in hearing aids with behind-

the-ear microphone placement is that it approximates the natural directivity patterns of the open ear, thereby helping to preserve horizontal localization.²³

EXTENDING SOUND QUALITY TO “FAR-FIELD” SOUND SOURCES

Hearing instruments are increasingly using wireless capabilities to put users in touch with other sound sources than what is picked up acoustically by the hearing instrument microphones. The ReSound proprietary 2.4 GHz digital wireless technology has provided the most convenient way for users to stream high quality audio from any sound source via Resound Unite wireless accessories, as it requires no body-worn streaming accessory. This system allows sound to be transmitted directly to the hearing instruments from a source at distances up to 7 m (30 feet).

In terms of sound quality, the 2.4 GHz proprietary technology offers many advantages. First, by designing a dedicated protocol for the wireless communication and streaming, it is possible both to provide stereo sound with a wide audio frequency bandwidth, and to minimize transmission delay to less than 20 ms. The short delay is especially important for hearing instrument users, who may receive a mix of sound from the hearing instrument microphones and streamed sound. For people with open fittings, direct sound will also enter into the equation. When sound is received from different sources there is a risk of timing issues which can result in poor sound quality, and with delays of over 40 ms or more an echo will begin to be heard. Delays of 40 ms or more are typical of the open standard Bluetooth wireless technology incorporated in most other manufacturers’ wireless streaming to hearing aids.

Another advantage of having already mastered digital wireless technology in the 2.4 GHz band is that it enabled ReSound to leap to a new type of functionality for hearing instruments: direct connectivity to consumer electronic devices. In a discussion of wireless technology in hearing instruments, Jespersen²² forecasted that the next generation of hearing instruments “will allow [a hearing aid user] to take phone calls through her hearing aids, and Skype with her grandchildren on her tablet using her hearing aids as the headset.” With the introduction of ReSound LiNX, this prediction becomes reality. This hearing instrument is the first to tap into a 2.4 GHz-based wireless streaming

protocol developed by Apple specifically for hearing instruments. Similar to the ReSound proprietary audio streaming, a power-efficient, high quality digital stereo audio experience is accessible directly from iPhone, iPad and iPod touch to ReSound LiNX hearing instruments. In addition, users can take advantage of a direct wireless signal to both hearing instruments for phone calls, which is the proven best way to optimize hearing on the phone.²⁴ Another helpful accessibility feature from Apple, “Live Listen”, lets the iPhone function as a remote microphone, picking up the voice or sound of interest near its source and streaming it in crystal clear quality directly to the user’s hearing aids.

SUMMARY

Sound quality is an essential consideration in hearing instruments. There is no better endorsement of sound quality than to say it is “natural-sounding;” ReSound strives to provide this experience to hearing instrument users with the Surround Sound by ReSound approach to signal processing. An impartial study of perceived sound quality in high-end hearing instruments found that ReSound technology was top-rated, supporting the ReSound philosophy. Natural sound quality relates to the holistic experience of hearing and perceiving sound, encompassing fidelity and qualitative dimensions as well as understanding speech. When sound is experienced as natural, the listener can effortlessly segregate and group the continuous stream of sound in the environment. A hearing instrument achieves natural sound quality by preserving spectral, dynamic, and temporal aspects of the input sound to an extent that higher level auditory and cognitive processing can interpret these physical attributes and construct auditory environments. In addition, good sound quality means not creating noticeable and disturbing artifacts. Surround Sound by ReSound combines advanced features that preserve and convey acoustic information to provide a rich, full sound picture so that wearers can connect with their actual environments. High quality connectivity to external sound sources is extended with the ReSound proprietary 2.4 GHz digital wireless technology. And with the “Made for iPhone” ReSound LiNX hearing instrument, users can for the first time experience power-efficient, high quality stereo sound streaming directly from their Apple devices to their hearing instruments.

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