THE NEURO-COMPENSATOR® TECHNOLOGY FOR HEARING AIDS

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Abstract

A novel approach to hearing-aid signal processing is described, which attempts to re-establish a normal neural representation in the sensorineural impaired auditory system. Most hearing-aid fitting procedures are based on heuristics or some initial qualitative theory. Despite the introduction of digital technology in 1995, traditional amplification theories such as loudness normalization, loudness equalization or maximal intelligibility have not contributed to a significant decrease of hearing aid user's dissatisfaction[2]. Recent research in characterizing sensorineural hearing loss has delineated the importance of hair cell damage in understanding the bulk of sensorineural hearing impairments. Neuro-Compensation, a novel methodology based on restoring normal neural representation after the sensorineural impairment is presented here. This approach has been used to design and manufacture a whole new generation of hearing-aids based on a new family of physiologically-based audio processing algorithms. The Neuro-Compensator® provides automated means of predicting the relative intelligibility of a given speech sample in normal hearing and hearing impaired subjects.

1. Neuro-Compensator®: A New Generation of Hearing Aids

There have been several advances in our understanding of the neurophysiologic basis of hearing impairment. The insight that hair cell damage alters the auditory system has profound effects on the design of hearing-aid systems to combat sensorineural loss. While conductive loss, which can arise after ossicle damage or an ear drum puncture, can largely be overcome with frequency-shaped linear amplification, the types of impairment associated with inner hair cell (IHC) and outer hair cell (OHC) damage require a new suite of algorithms. Up until the mid-1980s the mechanisms underlying the more prevalent type of impairment, hair cell loss, were not well understood. This led to a group of ad hoc algorithms, largely based on the discerned symptoms (spectrally shaped sensitivity loss, identification in noise problems) as opposed to the mechanisms underlying the symptoms.

The approach to evaluating hearing aids in the audiological field has been solely empirical. By using neuro-physiologically based auditory models, we show predictive measures for offline evaluation. These measures are consistent with experimental data on human performance. Furthermore, using auditory models, one can form a general hearing-aid algorithm design methodology, whose performance in simulations shows a high correlation with empirical evidence.

The processing of an acoustic signal by the peripheral auditory system can be summarized as follows. A sound signal is directed to the ear canal by the pinna (outer ear). The eardrum responds to the pressure wave by deflecting. This deflection causes the three small bones of the inner ear to move, producing a similar movement in the oval window of the cochlea. This vibration starts a travelling wave

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[2] MarkeTrak VII: Hearing Loss Population Tops 31 Million People, By Sergei Kochkin, PhD

in the Fluid of the cochlea. Up to this point, the system is well characterized by a linear transfer function, but beyond this point, the system is highly nonlinear. The travelling wave produces a peak displacement at some point along the cochlea that is a function of frequency and outer hair cell (OHC) undamping. OHCs are motile members that precisely modulate the basilar membrane; the basilar membrane is tonotopically mapped. Inner hair cells (IHCs) transduce the mechanical displacement of the basilar membrane to nerve firings. The OHCs undamping enhances the IHCs sensitivity and selectivity [29].

The loss of these hair cells produces symptoms such as elevated thresholds, loss of frequency selectivity, and loss of temporal discrimination [26, 23]. The consequences of hair cell damage for auditory discrimination are far-ranging, taking entire books to catalogue [26]. Necessary for future hearing-aid algorithms is a quantitative understanding of how IHC and OHC loss affects the processing of the auditory system and how that processing affects perception.

The objective of our research is to restore near-normal firing patterns in the auditory nerve, in spite of hair cell damage. While there is some evidence of reorganization in the mammalian auditory cortex [18] resulting from hair cell damage, there is no present evidence that the basic cortical circuitry does not work. That is, the processing in the brain that is eminently capable of segregation, streaming, and decoding, may still be able to function properly if the incoming signals are parcelled properly. A normal hearing process can be described as the block diagram in Fig. 1, where an input signal X is transformed by the auditory periphery, H, to produce a neural response Y. The auditory periphery is treated as a black box in many signal-processing applications.

The first step in our method of compensating for hair cell loss is to alter the input signal going into the impaired system such that after the impaired ear there is a normal neural representation; the algorithm to alter the input signal is called the Neuro-Compensator®.

2. Auditory Model

The key idea underlying the technique described below is to use models of the intact and damaged auditory system to evaluate the perceptual impact of hearing compensation algorithms offline. In our method the signal is pre-processed by the Neuro-Compensator, and then fed into the impaired model. The resulting neural representation is compared to the neural representation of the signal after the normal hearing model. Perceptual distortions from sensorineural impairment should be minimized by the Neuro-Compensator® by re-establishing in the impaired auditory system the normal pattern of neural firing.

The methodology therefore hinges on a detailed model of the peripheral auditory system. The auditory periphery model we use describes the function of the auditory system from the middle ear to auditory nerve, and includes a head-related transfer function that models outer ear. The auditory model itself comprises several sections, each providing a phenomenological description of a different part of auditory periphery function. The first section models middle ear filtering. The second section, labeled the "control path," captures the OHCs modulatory functions, and includes a wideband, nonlinear, time-varying, band-pass filter followed by an OHC nonlinearity (NL) and low-pass (LP) filter. This section controls the time-varying, nonlinear behavior of the narrowband signal-path basilar membrane (BM) filter. The control-path filter is designed to account for wideband nonlinear phenomena such as two-tone rate suppression. The third section of the model, labeled the "signal path", describes the filter properties and traveling wave delay of the basilar membrane (BM) (time-varying, narrowband filter), the nonlinear transduction and filtering of the inner hair cell, spontaneous and driven activity and adaptation in synaptic transmission (synapse model), and spike generation and refractoriness in the auditory nerve (AN).

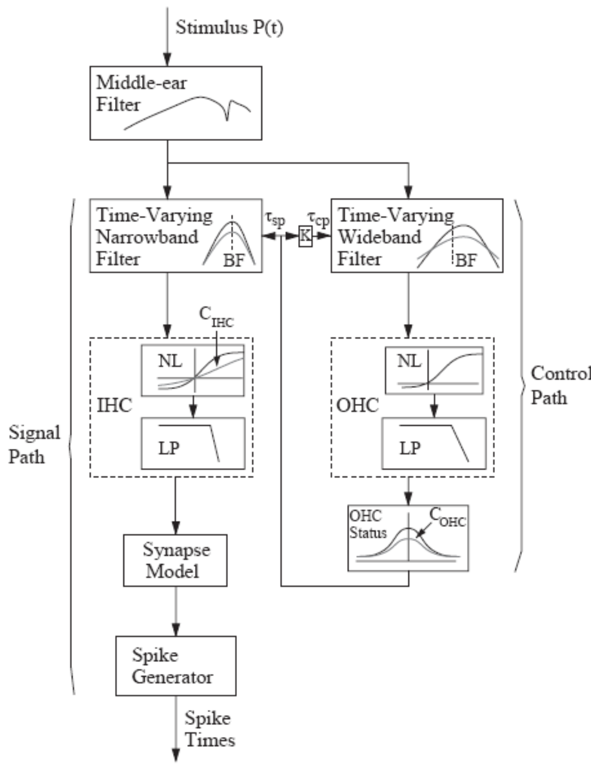

Fig.1: Block diagram of the computational model of the auditory periphery from the middle ear to the auditory nerve.

The Neuro-Compensator® auditory model is thought to correspond very closely with human physiology. This particular model has a long history of development and good fit to a wide range of empirical data. The auditory model can capture a range of phenomena due to hair cell nonlinearities, including loudness-dependent sensitivity and bandwidth modulation (as stimulus intensity increases the output response levels and frequency-tuning becomes broader), and masking effects such as two-tone suppression.

Additionally, the model incorporates critical properties of the auditory nerve response including synchrony capture in the normal and damaged ear and replicates several fundamental phenomena observed in electrophysiological experiments in animal auditory systems subjected to noise-induced hearing loss. For example, with OHC damage, high frequency auditory nerve fibers' tuning curves become asymmetrically broadened toward the lower frequencies and tend to become synchrony locked to lower frequencies. The model is capable of simulating auditory nerve responses in both a normal and damaged human auditory system accurately. The damaged model must be tuned to the parameters of a particular individual's hearing-impairment.

The success of the Neuro-Compensator strategy presented below depends upon the accuracy of the auditory model of the normal and damaged ear. Although an individual's auditory model can be tuned by extracting certain information from the audiogram, better methods can be used to estimate certain parameters. For instance, with additional test equipment and a substantial change in general audiology practice, the degree of inner and outer hair cell loss is better determined using noise-masked tones[3]. Given accurate measurements, the model could be tailored to compensate for many individual patterns of deficits.

3. Spectral Enhancement from Neural Compensation

The formation of the metric and validation of the strategy above provides for supervised training of any type of hearing aid algorithm. Since the new compensation strategy relies heavily on neural network type training, and is in essence trying to re-establish normal neural activity, the general processing strategy was coined Neuro-Compensation. A Neuro-Compensator® is any block whose weights are fitted to an individual's hearing loss through a training sequence that attempts to return the normal neural code. The training sequence is represented in Fig. 12.

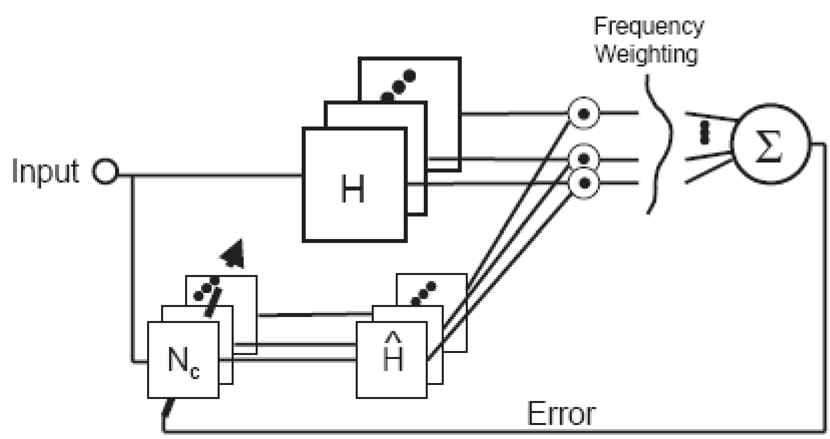

Fig.2: Block representation of the Neuro-Compensator® training sequence

Initial testing of our algorithm to establish the validity of our model-based approach was accomplished using idealized models of hearing impairment similar to those described in Byrne et al[4]. In each case, the output of the model was a time series, 230 ms long with a 22 050 Hz sample rate, of instantaneous neural spike rates across seven octave bands, starting at 125 Hz and ending at 8000 Hz.

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[3] B. Moore, M. Huss, D. Vickers, B. Glasberg, J. Alcantara, A test for the diagnosis of dead regions in the cochlea, Br. J. Audiol. 34 (4) (2000) 205–224

[4] D. Byrne, H. Dillon, T. Ching, R. Katsch, G. Keisder, Nal-nl1 procedure for 5tting nonlinear hearing aids: characteristics and comparisons with other procedures, J. Amer. Acad. Audiol. 12 (2001) 37–51

The Neuro-Compensator® is trained on a set of real life audio (speech) recordings, supervised by the difference between the output across a set of frequencies of the normal auditory model, H, and the output of the impaired auditory model, H. For each training iteration, the Neuro-Compensator® is tuned by adjusting the parameters of its gain function to minimize the error signal (i.e. force the damaged auditory nerve to send to the brain a signal that matches in strength and intensity the signal that would be sent by a normal nerve). More specifically, in the Neuro-Compensator® gain formula, the gain at each frequency, *i,* is affected by the level in all other *j* bands, leading to a large amount of parameters (weights) that need to be tuned at each training iteration. This particular gain formula is designed to replicate how masking phenomenon occur naturally in the human auditory system.

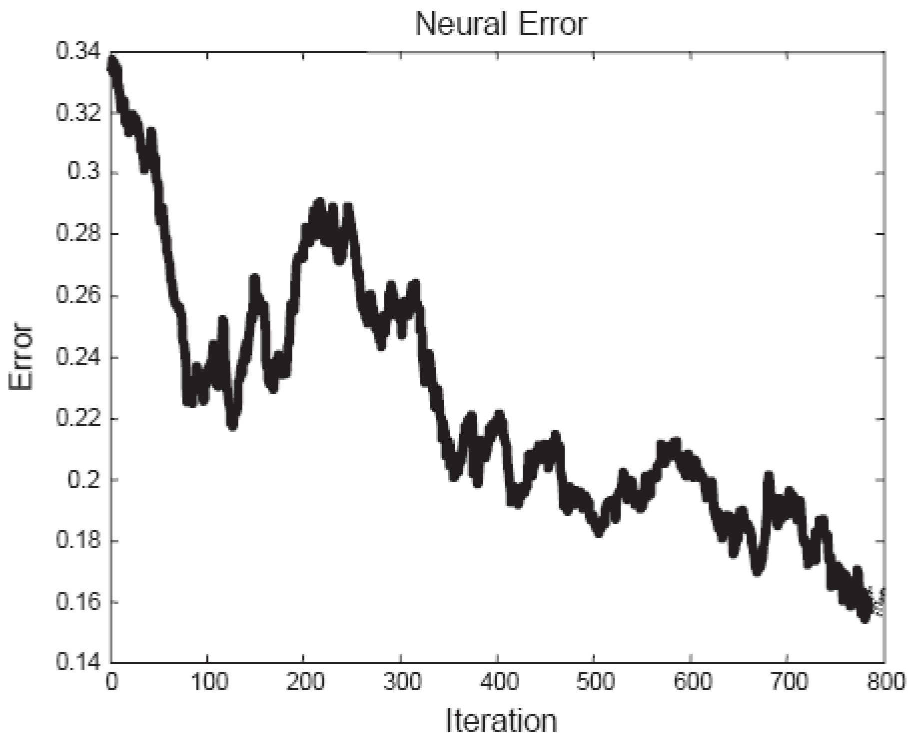

Fig.3: Training curve for the Neuro-Compensator® for 800 iterations. The error between the 'normal' and 'damaged' auditory models decreases gradually, showing how the hearing-aid amplification gain is gradually tuned to trigger proper stimuli to the brain.

During the offline Neuro-Compensator® training, a machine learning algorithm takes care of forcing all the Neuro-Compensator® weights to converge in the right direction. The machine learning algorithm we use is a stochastic optimization algorithm closely related to reinforcement learning and dynamic programming methods. It relies on the correlation between successive positive / negative parameter changes and objective function changes from trial to trial to stochastically decide in which direction to move each amplification parameter. Once the training error goes below an acceptable threshold, it is estimated that the Neuro-Compensator® amplification forces the damaged auditory model to generate a signal that matches the signal that would be generated by the normal auditory model. At that point, the training can be stopped; the amplification parameters are frozen and downloaded into the hearing-aid for real-time processing.

4. Results

The validity of restoring normal auditory nerve activity is tested by asking the question: would the standard fitting strategies, when applied to the input of the impaired model, result in optimal improvements in neural coding?

The standard hearing-aid processor to compare the Neuro-Compensator against is the WDRC (Wide Dynamic Range Compression) which has been an industry standard for some time. Both WDRC and the Neuro-Compensator were evaluated using *Neurograms* of various trials. The Neurogram is a spatio-temporal discharge pattern in the Auditory Nerve (AN). It is similar to a spectrogram, except it displays neural response as a function of fibre Characteristic Frequency (CF) and time.

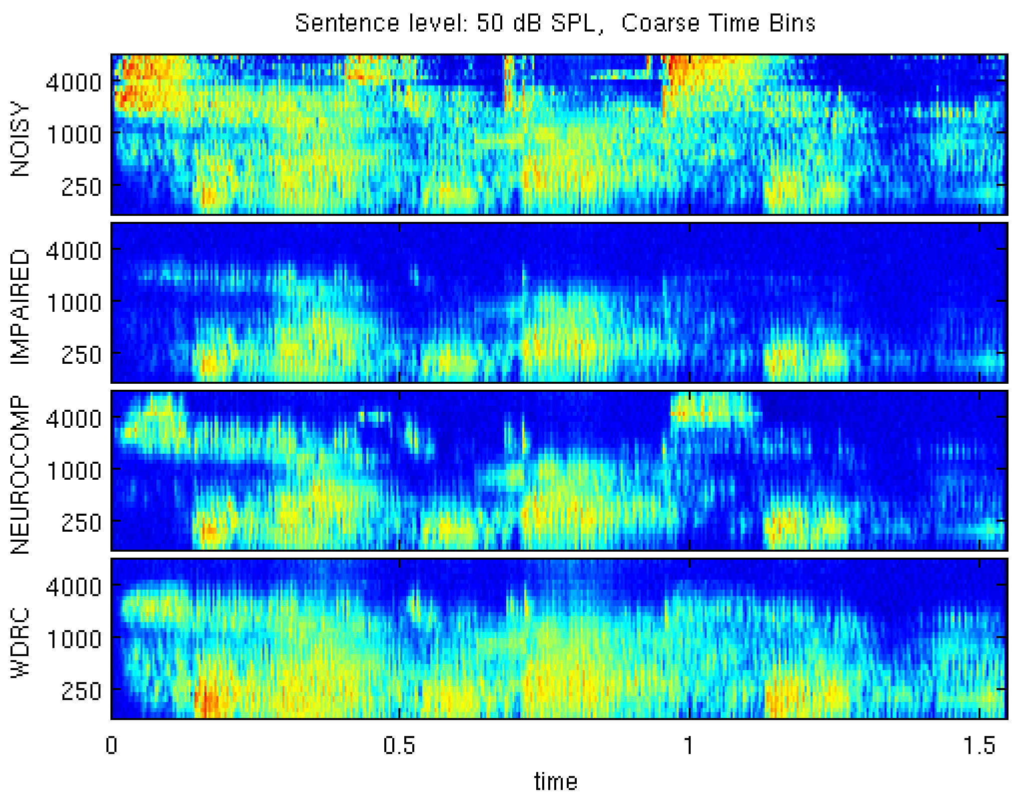

Fig.4: Comparing the WDRC and Neuro-Compensator Neurograms of an individual saying: "She had your dark suit in".

Both the Neuro-Compensator® and the WDRC algorithm attempt to force the patient's auditory system to reconstruct a nerve output that matches the normal neurogram as closely as possible. However, Fig.4 clearly indicates that the compression algorithm is sending an over-amplified signal to the brain, in the neural sense, while the Neuro-Compensator® succeeds in reconstructing much of the missing elements of the auditory nerve signal.

In addition to these simulation-based results, the Neuro-Compensator® was successfully tested in actual hearing aid applications to confirm these results.

5. Conclusion

The Neuro-Compensator® has a number of advantages over traditional approaches including the possibility of embedding suprathreshold knowledge in the design procedure. Traditional hearing aids calculate gain on a frequency-by-frequency basis determined solely by the 'channel' level, without taking into account masking effects due to cross-frequency and cross-temporal interactions. Such methods work well for restoring the detection of pure tones but fail to correct for many of the masking and interference effects caused by the loss of hair cell nonlinear tuning.

At this point, the design of compensation strategies based on restoring normal neural firing patterns seems to be a general strategy that can subsume historical empirical and recent physiological efforts. The idea that hearing-aid algorithm design can be viewed as neural compensation may open the door to novel concepts in assessing hearing impairment and scrutinizing hearing aid algorithms. To make this strategy complete some understanding of the true computational strategy of the auditory system is necessary.

While there have been a few attempts at formulating an intelligibility metric derived from the auditory neural code [8], we are still a long way from understanding the coding strategies employed by given populations of neurons [31]. Thus, the Neuro-Compensation strategy can be best used for comparative prediction of new hearing-aid algorithms, as well as being a very useful tool in their design. The Neuro-Compensator® proposed here has the capability, in principle, to restore a number of the filtering capabilities intrinsic to the cochlear hair cells.

About VitaSound

Founded in 2008 by experienced professionals from the audio and hearing industries, VitaSound is dedicated to developing and commercializing hearing technologies and products geared towards total hearing healthcare, including protection and preservation of hearing. Unique and innovative technologies such as Neuro-Compensator® are the foundations of the company's product offerings. For more information, visit www.vitasound.com.