RECRUITMENT COMPENSATION AS A HEARING AID SIGNAL PROCESSING STRATEGY

Jont B. Allen (www.research.att.com/info/jba)

AT&T Labs–Research, 180 Park Ave
Florham Park, New Jersey 07932

ABSTRACT

Although Fowler is commonly given credit for discovering recruitment [14], Steinberg and Gardner at Bell Labs [25] were the first to understand its true significance. Today recruitment is poorly understood, and is generally *misdefined* as the *abnormally rapid growth of loudness*. It is not well known that loudness in sones does *not* grow more rapidly in the recruiting ear; rather it is the intensity of an equally loud tone (i.e., the loudness–level in phons) that grows more rapidly. Regardless of the definition, recruitment is the most basic manifestation of sensory–neural hearing loss. Recruitment is due to the loss of outer hair cell (OHC) function. The sound–detecting inner hair cells (IHC) within the cochlea have a limited dynamic range of less than 60 dB. The OHCs nonlinearly compress the dynamic range of the signal excitation to the IHC, extending its dynamic range. Thus the normal function of OHCs plays a critical role in loudness and speech coding. Distortion product otoacoustic emissions (OAE) are an objective measure of OHC nonlinear compression, while loudness growth is a subjective measure. This report discusses the application of multi-band compression (MBC) to the compensation of loudness recruitment. This technology was "reinvented" at Bell Labs between 1983 and 1987 and is now sold by the ReSound Corporation. Our basic strategy with multi-band compression is to restore the normal dynamic range which is lost due to OHC misfunction. I describe why MBC works and what the hair cells do. In the oral presentation I shall describe how the OHCs might act as compressors (see my web site). Finally I review the history of the MBC hearing–aid development at Bell Labs.

1. LOUDNESS GROWTH

Acoustical signal *intensity* is defined as the flow of acoustic energy. *Loudness*, in *sones* or *loudness units* (LU),[1] is the name given to the perceptual attribute corresponding mainly to acoustic signal intensity. Loudness depends in a complex manner on a number of acoustical variables, such as intensity, frequency, spectral bandwidth, and on the temporal properties of the stimulus, as well as on the mode of listening (e.g., in quiet or in noise, binaural or monaural stimulation). Iso–loudness contours, which define the *loudness–level*, or *phon* scale, were first determined in 1927 by Kingsbury [15, 9, (p. 227)]. These curves describe the relation between equally–loud tones or narrow bands of noise at different frequencies.

In 1924 Fletcher and Steinberg published an important paper on the measurement of the loudness of speech signals [13]. In this paper, when describing the growth of loudness, the authors state

> the use of the above formula involved a *summation of the cube–root of the energy rather than the energy.*

This cube–root dependence had first been described by Fletcher the year before [8].

Today, any power–law relation between the intensity of the physical stimulus and the psychophysical response is referred to as *Stevens' law* [23, 4]. Fletcher's 1923 loudness growth equation established the important special case of loudness for Stevens' approximate, but more general, psychological "law." Weber's "law" states that $\Delta I/I$ is constant, where I is the intensity, and ΔI is the just noticeable difference (JND) in the intensity. Weber's law is known to be only approximately correct for pure tones [22]. Fechner's "law," that loudness is proportional to the log of the intensity, is based on the idea that the JND may be integrated to obtain a psychophysical scale, which in this case is loudness [6]. By 1961, Stevens was arguing that Fechner's law was fundamentally incorrect [26]. As described previously, by 1924 Fletcher had shown that Fechner's law did not hold for speech signals (they discusses this point in the 1924 paper) and for tones in 1933. The relation between the loudness growth law and the JND has a long history [24, 4].

2. COCHLEAR NONLINEARITY: HOW?

What is the source of Fletcher's cube–root loudness growth (i.e., Stevens' Law)? Today we know that the basilar membrane motion is nonlinear, and that cochlear outer hair cells (OHC) are the source of the basilar membrane nonlinearity, resulting in the cube–root loudness growth observed by Fletcher.

From noise trauma experiments on animals and humans, we may conclude that recruitment (abnormal loudness growth) occurs in the cochlea [7]. In 1937, Lorente de No theorized that recruitment is due to hair cell damage [19]. Animal experiments have confirmed this prediction and have emphasized the importance of outer hair cell (OHC) loss [18, 17]. This loss of OHCs causes a loss of the basilar membrane compression as first described by Rhode in 1971 [2, 21, (p. 291)]. It follows that the cube–root loudness growth starts with the nonlinear compression of basilar membrane motion due to stimulus dependent voltage changes within the OHC.

We still do not know precisely what controls the basilar membrane nonlinearity, although we know that it is related to outer–hair–cell length changes, which are controlled by the OHC membrane voltage. This voltage is determined by shearing displacement of the hair cell cilia by the tectorial membrane. Based on ear canal impedance measurements, the most likely cause of nonlinear basilar membrane mechanics is due to changes in the microme-

[1] Sones and LU are related by a scale factor. One sone is 975 LU.

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chanical impedances within the organ of Corti, which result from OHC length changes. This conclusion logically follows from ear canal impedance measurements expressed as the nonlinear power reflectance, defined as the retrograde to incident power ratio [5], which shows that the relative local basilar membrane impedance is stimulus–level dependent.

3. COCHLEAR NONLINEARITY: WHY?

This leaves unanswered *why* the OHCs compress the signal on the basilar membrane. The answer to this question has to do with the large dynamic range of the ear.

IHC dynamic range. Based on the Johnson (thermal) noise within an inner hair cell, it is possible to accurately estimate a lower bound on the RMS voltage within the inner hair cell. From the voltage drop across the cilia we may estimate the upper dynamic range of the cell. The total dynamic range of the IHC must be less than this ratio, namely less than 65 dB. The dynamic range of hearing, on the other hand, is frequently stated to be 120 dB. Thus, *the inner hair cell does not have a large enough dynamic range to code the dynamic range of the input signal.* Spread of excitation models and neuron threshold distribution of neural rate do not address this fundamental problem. Nature's solution to this problem is the OHC–controlled basilar membrane compression.

The formula for the Johnson RMS thermal electrical noise voltage $|V_c|$ due to cell membrane leakage currents is given by

$$|V_c|^2 = \int_{-\infty}^{\infty} \frac{2kTRdf}{1+(2\pi fRC)^2}, \tag{1}$$

where R is the cell membrane leakage resistance and C is the membrane capacitance C. It follows that

$$|V_c| = \sqrt{\frac{4kT}{C}}. \tag{2}$$

The cell capacitance has been determined to be about 9.6 pF for the IHC [16]. Thus from Eq. 2 we find that $V_c = 21\ \mu V$.

Although the maximum DC voltage across the cilia is 120 mV, the maximum RMS change in cell voltage that has been observed is about 30 mV (I. J. Russell, personal communication). The ratio of 30 mV to the noise floor voltage (21 μV), expressed in dB, is 63 dB. Thus it is impossible for the IHC to code the 120 dB dynamic range of the acoustic signal. Because it is experimentally observed that, taken as a group, IHCs *do* code a wide dynamic range, the nonlinear motion of the basilar membrane must be providing compression within the mechanics of the cochlea prior to IHC detection.

4. LOUDNESS ADDITIVITY

In 1933, Fletcher and Munson published their seminal paper on loudness. It details *1)* the relation of iso–loudness across frequency (loudness–level or phons), *2)* their loudness growth argument (in loudness–units, or sones), *3)* a model showing the relation of masking to loudness, *4)* and the basic idea behind the critical band (critical ratio) [12]. The arguments they used were elegant, and the results were important.

Rather than thinking directly in terms of loudness growth, they tried to find a formula describing how the loudnesses of several stimuli combine. From loudness experiments with low– and high–pass speech and complex tones [13, 9], and other unpublished experiments over the previous 10 years, they found that loudness adds.

Today this model concept is called *loudness additivity*. Their hypothesis was that when two equally loud tones that do not mask each other are presented together, the result is "twice as loud." This method is sometimes referred to as the *indirect method.* Fletcher verified his additivity hypothesis by use of the *direct method* in which subjects are asked to turn up the sound until it is "twice as loud." A further verification of this assumption lies in the predictive ability of this additivity assumption. For example, they showed that 10 tones that are all equally loud, when played together, are 10 times louder, as long as they do not mask each other. Fletcher and Munson found that loudness additivity held for signals "between the two ears" as well as for signals "in the same ear." When the tones masked each other (namely, when their masking patterns overlapped), additivity still held, but over an attenuated set of patterns [12]. Their 1933 model is fundamental to our present understanding of auditory sound processing.

Fletcher's working hypothesis was that each signal is *nonlinearly compressed* by the cochlea, neurally coded, and the resulting cochlear nerve neural rates are added. The 1933 experiment clearly showed how loudness (i.e., the neural rate, according to Fletcher's model) adds. Fletcher and Munson also determined the *compression function* $G(p)$. Their experiment did not prove that $G(p)$ must result from the nonlinear action of the cochlea but it was consistent with it.

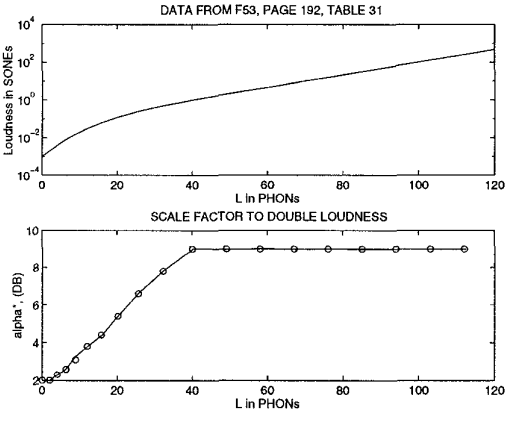

Figure 1: This figure shows the loudness growth and α^* from p. 192, Table 31 [11] as a function of the loudness level, in phons. When α^* is 9 dB, loudness grows as the cube–root of intensity. When α^* is 3 dB, loudness is proportional to intensity.

From their formulation Fletcher and Munson found that at 1 kHz, and above 40 dB SPL, the pure tone loudness G is proportional to the cube–root of the signal intensity ($G(p) = (p/p_{\text{ref}})^{2/3}$, because two equally loud simultaneous tones, are equally loud to a single tone 9 dB greater in intensity. In other words, if the pressure p is increased by 9 dB, the loudness is doubled. Below 40 dB SPL, loudness was frequently assumed to be proportional to the intensity ($G(p) = (p/p_{\text{ref}})^2$, $\alpha^* = 2^{1/2}$, or 3 dB).[2]

[2]The parameter α^* is the gain applied to the pressure p to double the loudness.

Figure 1 shows the loudness growth curve and α^* given in [11, Table 31, page 192]. As may be seen from the figure, the measured value of α^* at low levels was not 3 dB, but was closer to 2 dB. Fletcher's statement that loudness is proportional to intensity (α^* of 3 dB) was an idealization that was appealing, but not supported by actual results. The basic idea, and the cube–root dependence on intensity above 40 dB SPL, was first published in Fletcher (1923).

5. RECRUITMENT AND THE RATE OF LOUDNESS GROWTH

In Fig. 2 we show a normal loudness growth function along with a simulated recruiting loudness growth function. It is necessary to plot these functions on a log-log (log–loudness versus dB SPL) scale because of the dynamic ranges of loudness and intensity. The use of dB and log–loudness have resulted in a misinterpretation of recruitment. In the figure we see that for a 5 dB change in intensity at 60 dB SPL, the loudness changes by 2.22 sones in the normal ear and 0.585 sones in the recruiting ear. If we define $\beta = 10\log(I/I_{\text{ref}})$ as the relative intensity in dB SPL, then $d\beta = 10dI/I$. Thus at a given intensity, the ratio of two slopes, defined in terms of dB SPL ($dL/d\beta$), will be the same as those defined in terms of intensity (dL/dI).

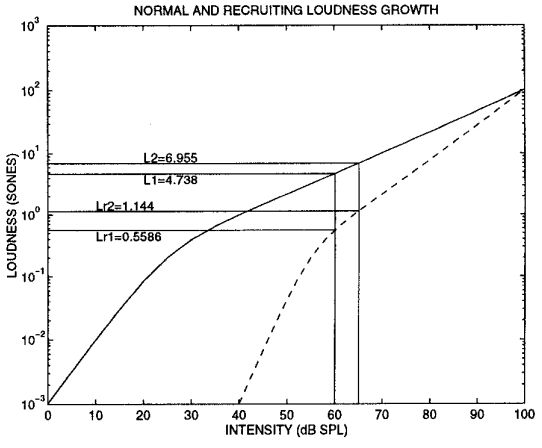

Figure 2: We show here a recruitment type loss corresponding to a variable loss of gain on the dB scale. The upper curve corresponds to the normal loudness curve whereas the lower curve corresponds to a simulated recruiting hearing loss. For an intensity level change between 60 and 65 dB, the loudness change is smaller for the recruiting ear. The belief that the loudness slope in the damaged ear is greater led to the belief that the JND in the damaged ear should be smaller (e.g., this was the rationale behind the SISI test) [20, page 160]. Both conclusions are false.

The relative loudness in the recruiting and normal ear changes by a factor of 0.585/2.22 = 0.26 in this example. Although the visual slope of the log–loudness growth function is steeper for the recruiting ear, the computed slope in sones per watt (dL/dI) is smaller. When the loudness growth is plotted as loudness–level (i.e., in terms of phons) the computed slope is greater. Thus it is proper to define recruitment as "the abnormally rapid growth of loudness–level." In fact this is frequently how recruitment is described, in terms of loudness–level. However, the formal definition is given in terms of loudness. Thus, the misunderstanding results from confusing the phon and sone scales.

Steinberg and Gardner clearly understood what they were dealing with, as is indicated in the following quote [25, page 20]

> Owing to the expanding action of this type of loss it would be necessary to introduce a corresponding compression in the amplifier in order to produce the same amplification at all levels.

This model of hearing and hearing loss, along with the loudness models of Fletcher [12], are basic to an eventual quantitative understanding of cochlear signal processing and the cochlea's role in detection, masking, and loudness in normal and impaired ears. The work by [10] and [25], and work on modeling hearing loss and recruitment [1], support this view.

6. MULTI–BAND COMPRESSION

Ed Villchur recognized the importance of Steinberg and Gardner's observations, and vigorously promoted the idea of compression amplification. Supporting the cost of the research from his very successful loudspeaker business, he contracted David Blackmer of **dbx** to produce a multi-band compression hearing aid for experimental purposes. Using the experimental multi-band compression hearing aid, Villchur experimented on hearing impaired individuals, and found that Steinberg and Gardner's predictions were correct [27].

Fred Waldhauer, an analogue circuit designer of some considerable ability, heard Villchur speak about his experiments in multiband compression. After the breakup of the Bell System in 1983, Waldhauer proposed to AT&T management that Bell Labs design and build a multi-band compression hearing aid as an internally funded venture. I soon joined Waldhauer in this proposed venture, which was internally funded some months later.

While Waldhauer and his team looked into new analogue circuit designs, my group did the algorithm design and hardware and software simulations of several signal processing architectures. Eventually we built a digital wearable hearing aid prototype based on a subset of these early designs. It quickly became apparent that the best processing strategy compromise was a two–band compression design that was generically similar to the Villchur scheme. With lots of help from my colleague Joe Hall of AT&T, and Patricia Jeng, Harry Levitt, and many others from CUNY, we designed a fitting procedure, and ran several field trials.

AT&T licensed its hearing aid technology to ReSound on February 27, 1987. Four AT&T people went to ReSound to continue the development. I continued to interact with them as a member of the ReSound Scientific Advisory Board. Eventually, after solving many difficult practical problems, Fred's newly formed ReSound team was successful in finalizing the analogue compression processing chip that is now the heart of the ReSound hearing aid. The chip design and the loudness–based LGOB (Loudness Growth in Octave Bands) fitting procedure [3] turned out to be the most challenging aspects of the final hearing aid.

It was, and remains, difficult to show quantitatively the nature of the improvement of MBC in a way that can convince the world. It is probably fair to say that only with the success of ReSound's MBC hearing aid in the marketplace has the world come to accept Villchur's claims. Why is this? I think the problem has to do with the two views of what MBC is and how it works. These views strongly influence how people think about compression. They are the *articulation index (AI) view* and the *loudness view*.

The AI–view is based on the observation that speech has a dynamic range of about 30 dB in 1/3 octave frequency bands. The

assumption is that the speech AI will increase in a recruiting ear, as the compression is increased, if the speech is held at a fixed loudness. This view has led to unending comparisons between the optimum linear hearing aid and the optimum compression hearing aid.

The loudness–view is based on restoring the natural dynamic range of all sounds to the listener to provide the impaired listener with all the speech cues in a more natural way. Soft sounds for normals should be soft for the impaired ear, and loud sounds should be loud. According to this view, loudness is used as an index of audibility, and complex arguments about JNDs, speech discrimination, and modulation transfer functions just confound the issue. This view is supported by the theory that OHCs compress the IHC signals.

Neither of these arguments deals with important and complex issues such as the changing of the critical band with hearing loss, or the dynamics of the compression system. The analysis of these important details are interesting only *after* the signals are placed in the audible range. Imagine for example a listening situation with a soft speaker and a loud speaker, having a conversation. In this situation, the compressor gain must operate at syllabic rates to be effective. The use of multiple bands ensures that a signal in one frequency band does not control the gain in any other band.

When properly designed and fitted, MBC signal processing has proven to be *the* most effective speech processing strategy we can presently provide. The reason it works is because it supplements the OHC compressors provided by Mother Nature, which are damaged in sensory–neural hearing loss.

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