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The Growth of Loudness Functions Measured in Cochlear Implant Listeners Using Absolute Magnitude Estimation and Compared Using Akaike's Information Criterion

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Abstract— **The input/output function for acoustic hearing can be characterized by the growth of loudness with sound pressure level and generally follows a compressive power law. In contrast, in electric hearing, loudness reportedly is an expansive function of applied electrical current but the specific shape of the function has not been fully determined. Loudness growth models have implications for the implementation of cochlear implant speech processors. Having an appropriate loudness growth model is important to cochlear implant users because they have a small dynamic range of hearing compared to normal hearing listeners. To compensate for this, appropriate models of loudness are necessary for the design of cochlear implant speech processors. It is also necessary to understand how loudness is encoded and may affect the relative performance in speech recognition. Currently, there is no consensus on the actual shape of the loudness growth function, with power or exponential functions being suggested. In this study psychophysical loudness growth measures were obtained in twelve adult cochlear implant listeners, using the method of absolute magnitude estimation and production. Best-fit loudness growth functions as determined by Akaike's Information Criterion (AIC) method for finding the best-fit loudness model, seem to show a difference in the loudness growth functions across subjects and across electrode pairs within individual subjects. The range of functions observed is greater than previously reported and goes from linear to expansive, suggesting that individual variations in dynamic range should be incorporated in the design of cochlear implant sound processors.**

I. INTRODUCTION

The growth of sensation magnitude with stimulus intensity is a fundamental property of sensory systems. Beginning with the classical studies by G.T. Fechner and S.S. Stevens, a wide variety of studies in several sensory systems have revealed that the growth of sensation, including loudness, is fundamentally related to the stimulus intensity by a power law. For a power law, $y = a(x)^b$ where in acoustic hearing y is perceived loudness, x is the sound pressure level (SPL), and b is an exponent approximately equal to 0.6, (i.e. the function is compressive). However, because cochlear implants bypass the auditory periphery and stimulate the auditory nerves directly, no consensus has been made on the shape of the growth of loudness magnitude with stimulus intensity for cochlear implant stimulation. Various studies have suggested that for cochlear implant listeners presented with pulsatile stimuli, the shape of the loudness functions grow as an expansive nonlinear function of stimulus current. Loudness growth functions for cochlear implant listeners have been described as being best-fit by power functions in which the exponents are greater than 1, when both loudness and current are plotted on logarithmic scales (i.e. [12]). Loudness growth for electrical stimulation in cochlear implants was described by a power function with a range of exponents around 2.72 to 3.5 [6,11].The loudness growth functions have also been reported to grow exponentially with stimulus current so that $y=ae^{bx}$, [14,16].

Electrical loudness functions have also been described by combinations of both power and exponential functions [10] or by utilizing a forth-order polynomial, which follows the equation $y=a_0 + a_1x^1 + a_2x^2 + a_3x^3 + a_4x^4$, [4]. The polynomial fit may be a convenient way to approximate individual variations in how loudness grows with current. It has been suggested that individual variations in the loudness growth functions may be due to variations in neural processes that accompany cochlear implant stimulation. These variations may be the result of spatial distribution of surviving neurons and/ or contributing neurons, variations in the distributions of electrical fields due to electrode placement, and stimulation mode [9]. While a higher-order polynomial may provide the best-fit approximation of individual variations in loudness functions in electric hearing, higher-order polynomial fits are more sensitive to perturbations in the data. There is a trade-off between goodness-of-fit and parsimony in model selection, but it may be more practical to use a more simplistic model approach.

Electrical stimulation of the auditory nerve, as in cochlear implant listening, bypasses the peripheral sensory organ to reveal the central processes of the auditory system. Zeng and coworkers [15,16,17,18] suggest that electrical hearing bypasses peripheral cochlear mechanics to reveal an expansive nonlinear loudness growth function. Not only can the understanding of the growth of sensation magnitude with stimulus intensity provide a better understanding of neural processes, it also may have clinical implications. It has also been suggested that the best speech recognition performance occurs when the normal loudness growth function was restored and that misrepresentations of the normal loudness growth function resulted in a significant decrease in speech performance [1,2,5,6,13].

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II. METHODS

A. *Subjects*

Twelve adult CI listeners served as subjects in these experiments. Four of these subjects utilized a Cochlear Nucleus 22 (subjects S2, S9, S3, S12), seven subjects use a Nucleus 24 (S4, S5, S6, S7, S8, S10, and S11), and one subject had one Nucleus 22 (S1a) and a Nucleus 24 (S1b). The subjects ranged from 18 to 70 years of age. Subjects S3, S11, S12, S4, S10, S6, S8, and S5 were all postlingually deafened, and subjects S1a, S2, S9, and S7 were prelingually deafened.

B. *Stimulus*

Stimuli were delivered through a custom research interface (House Ear Institute Research Instrument: HEINRI), software developed by Mark Roberts and the NIC Research Interface. Both systems were calibrated to check consistency for signal delivery. Signals consisted of trains of 200-μsec/phase biphasic pulses with a 20-μsec silent interval between pulse phases, presented in bipolar (BP + N) mode. Electrode pair (A, B) therefore indicates current flow between electrode A and electrode B = A + N+1 where the lower numbered electrode, A, serves as the source for the initially negative current pulse and the return is via electrode B. Electrode pairs utilized in this study were typically 4,7; 10,13; 16,19; each representing a narrow area of stimulation from regions of the cochlea representing the base, mid-cochlea, and apex, respectively. Bipolar electrode pair 10,16 was also used to measure effects of wider current spread along the cochlea. Signals were 100-msec-long, 500-Hz pulse trains. Signal thresholds were determined either by asking the subject to adjust the current to a just audible level or using a 3-interval forced-choice paradigm, with feedback, converging at the 79.4% correct point [8] Maximum Allowable Levels (MALs) were determined by asking subjects to adjust the current to the maximum level that they felt was allowable for experimentation with the particular electrode configuration. Although loudness appeared to play a key role in the choice of MAL, subjects reported that their MAL was also determined by a variety of unacceptable sensations and physiological responses that would be produced by higher currents. The dynamic range was defined as the range of current levels between measured levels of threshold and MAL for each electrode pair considered in this study. Two psychophysical methods were used to measure loudness sensation for several current levels within the dynamic range for each electrode pair utilized in this study; absolute magnitude balance (AMB) and cross modality matching (CMM); (e.g. [19], [3]). Listeners were instructed to match loudness of CI stimulation and numbers by using their internal, natural scale to evaluate loudness. The second analogous experiment was performed using CMM between loudness and line length. Currents of adjustable magnitude were presented under dedicated computer control, with current changing in steps of one clinical unit when controlled by the subject. Lines of adjustable length were presented under computer control, using a second dedicated computer, and projected on the wall of a dimly lit room against a diffuse and relatively featureless background. Subjects sat 265 cm from the wall and observed a thin line projected on the wall at a height of 231 cm. Line length could change in small steps of approximately 0.2% of the maximum length of 143 cm. Either subject or experimenter would then control each computer to change the magnitudes of the sound levels or the line lengths.

Data Analysis

Various curve fit models were fit to the loudness functions, such as linear, power, and exponential fit, based on previous theoretical considerations. SPSS statistical software package was used for curve-fitting and statistical analyses. Linear, power, and exponential functions were fit using nonlinear regression and best-fit functions were derived for each individual loudness function using Akaike's Information Criterion (AIC), which utilizes a combined maximum likelihood and information theoretical approach and was used to determine the best fit function by determining how well the curve fits the data. AIC allows the determination of the model that is most-likely correct best fit of the data, and it quantifies how much more likely it is to fit the data than another comparison model [7].

III. RESULTS

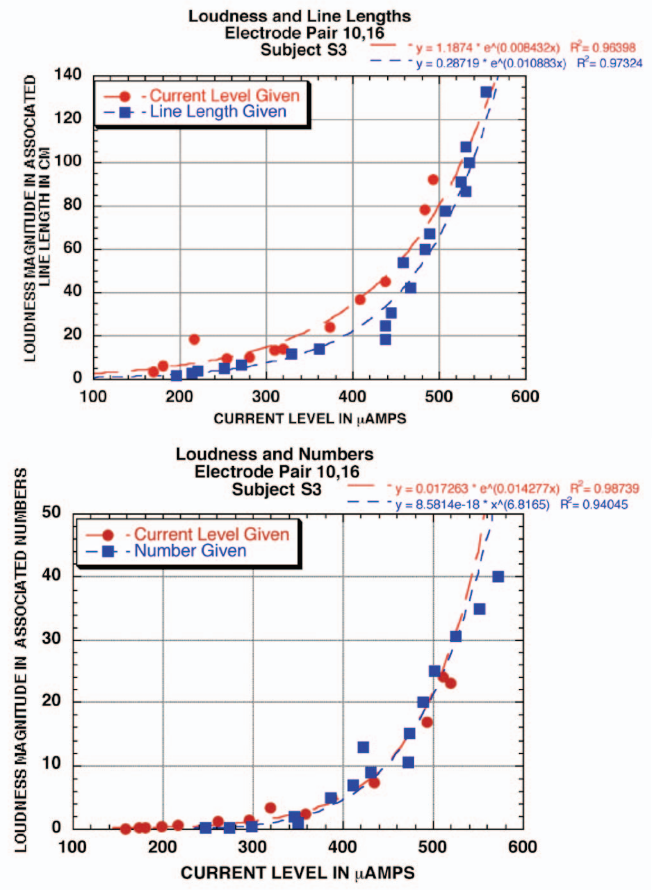

Fig. 1 The results from subject S3 demonstrate expansive non-linear functions. Shown are the results from both loudness and line length (top) and loudness and numbers (bottom) for the same subject and electrode pair (10,16).

According to the results from the AIC analysis, the shape of the loudness functions indicated that there were two classes of people found; linear and expansive (power and exponential best fit functions). Subjects S1a, and S1b and S2 seem to mostly demonstrate best-fit linear loudness functions, whereas subjects S3, S4, S5, S6, S7, S8, S9, S10, S11, and S12 mostly demonstrate best-fit expansive functions (power, exponential). An example of the results for subject S3 are shown in Fig. 1. For the electrode pair (10,16), the subject shows growth of loudness that is best fit by an expansive function for both magnitude estimation and production. The opposite is true for subject S1, whose results are shown in Fig. 2. Here, the subject's growth of loudness is best fit by a linear function for both magnitude estimation and production. The results for subject S1 are consistent across the subject's bilateral cochlear implants.

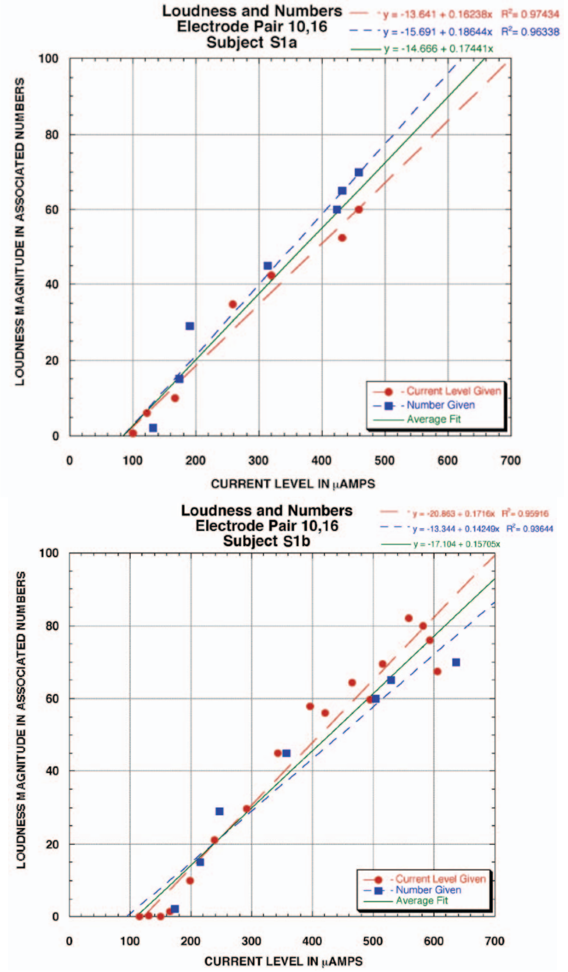

Fig. 2 Growth of loudness measured for subject S1 measured on electrode pair (10,16) for bilateral cochlear implants (top: right side, bottom: left side). The results demonstrate growth of loudness that is best fit by a linear function.

IV. DISCUSSION

Current cochlear implant speech processors assume a uniform, expansive loudness growth function for all electrodes and subjects. Results show that the shapes of the loudness functions vary both across subjects and within an individual subject for individual electrode pairs. These AMB and CMM results may also suggest that the shape of the loudness function is molded in part by the nature and processing of auditory input prior to implantation. These results may indicate that speech processors may need to be redesigned to take into account individual differences in loudness growth to maximize listening performance for cochlear implant listeners.

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