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LOUDNESS OF SIMPLE AND COMPLEX STIMULI IN ELECTRIC HEARING

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In a earlier study we showed that loudness function depends on stimulus frequency for simple sinusoidal and pulsatile stimuli in cochlear implants. Loudness is an exponential function of stimulus amplitude for high frequencies (>300 Hz) and a power function for low frequencies (<300 Hz). Two experiments were conducted to extend our previous work in eight Ineraid cochlear implant subjects. First, loudness functions were measured by means of a magnitude estimation technique for simple sinusoidal stimuli. Stimuli were 100- and 1,000-Hz sinusoids. Stimuli had a duration of 300 milliseconds and were presented at amplitudes representing 10%, 30%, 50%, 70%, and 90% of the dynamic range. Loudness estimates were best fit by an exponential function for the 1,000-Hz sinusoid and by a power function for the 100-Hz sinusoid. The estimation result is consistent with previous results that were obtained with a loudness balance technique. In a second experiment, loudness functions were studied for modulated stimuli, in which a 1,000-Hz sinusoid was modulated by a 100-Hz sinusoid at either 50% or 100% modulation depth. A linear loudness-balance function was obtained between the modulated stimuli and a 1,000-Hz sinusoidal standard, indicating that the modulated stimuli have the same exponential loudness function as the 1,000-Hz carrier despite the 100-Hz modulator. This result has important implications for speech processor design, because many devices use low-frequency speech envelopes to modulate a high-frequency carrier. This result also provides a psychophysical basis for the logarithmic amplitude transformation in commonly used speech processors to compress the wide acoustic dynamic range into a narrow electric dynamic range while preserving normal loudness function.

INTRODUCTION

One of the fundamental percepts in hearing is loudness, which is defined as "that attribute of auditory system in terms of which sounds may be ordered on a scale extending from soft to loud."[1] The acoustic attribute most relevant to loudness is sound amplitude. It has been established in acoustic hearing that loudness is a power function of the sound amplitude, which is termed "Stevens's law" and presumably reflects the amplitude compression of the sensory end organs.[2]

In electric hearing with cochlear implants, the nonlinear cochlea is bypassed and the auditory nerve is stimulated directly. Therefore, quantifying the loudness function in electric hearing is not only theoretically interesting in terms of understanding normal mechanisms of loudness perception, but also of practical importance in terms of implant speech processor design. Such a processor must compress a large range of acoustic amplitude into a small range of electric amplitude while preserving normal loudness variations. The form of the loudness function in electric hearing was not well understood until recently, when direct comparison in loudness growth between acoustic and electric hearing was possible in some implant subjects with residual acoustic hearing in their nonimplant ear.[3-5] Using a loudness balance technique, Zeng and Shannon[6] showed that loudness in electric stimulation depends on stimulus frequency; loudness is an exponential function of the stimulus amplitude for high frequencies (>300 Hz) and a power function for low frequencies (<300 Hz).

In this study, we describe two experiments to confirm and extend our previous work. The first experiment used the technique of magnitude estimation to derive directly the loudness functions of low-frequency and high-frequency sinusoidal stimuli. If the previous work holds, then a power function of loudness growth would be predicted for the low-frequency stimulus, and an exponential function would be predicted for the high-frequency stimulus. The second experiment used a low-frequency sinusoid to amplitude-modulate a high-frequency sinusoidal carrier.

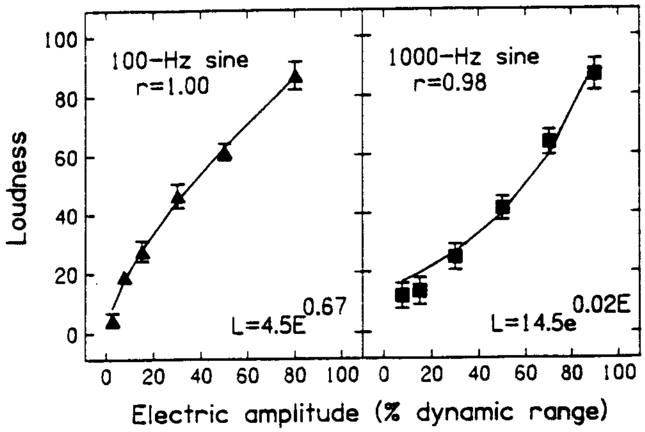

Fig 1. Loudness functions for sinusoidal stimuli of 100 Hz (left panel) and 1,000 Hz (right panel). Data were average of eight Ineraid cochlear implant listeners and were obtained by technique of magnitude estimation. Loudness function for 100-Hz sinusoid (sine) is best described by power function (r = 1.00), and 1,000-Hz sinusoid is best described by exponential function (r = .98).

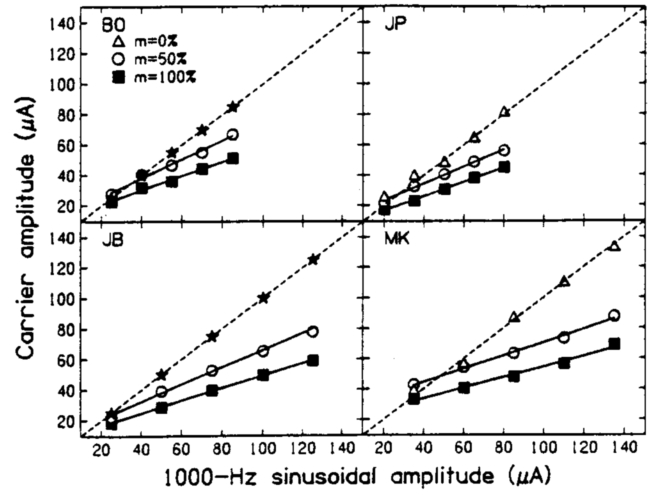

Fig 2. Loudness balance functions between amplitude-modulated stimuli and 1,000-Hz sinusoidal standard in four individual implant subjects. Modulated stimuli consisted of 1,000-Hz sinusoidal carrier and 100-Hz sinusoidal modulator: $A_m = A_c(1-m\cos 2\pi f_m t)\sin 2\pi f_c t$, where A_m is instantaneous amplitude of modulated stimulus, A_c is carrier amplitude, m is modulation depth, f_m = 100 Hz, and f_c = 1,000 Hz. Dashed line in each panel represents control condition in which 1,000-Hz sinusoid was loudness-balanced to itself. Solid line represents best fit of linear balance function (r > .98 for all conditions).

The loudness function of the modulated stimuli was derived by loudness balance between the modulated stimuli and a simple sinusoidal stimulus. If the low-frequency envelope is important, then the loudness of the modulated stimulus would follow the power function of the low-frequency modulator; if the high-frequency fine structure is important, then it would follow the exponential function of the carrier. The outcome of the second experiment has important implications with regard to speech processor design, because many devices extract low-frequency envelopes in speech sounds and use them to modulate a high-frequency carrier.[7] Whether the loudness function of the modulated stimuli follows the function of the modulator or the carrier will determine which acoustic amplitude compression algorithm is needed to preserve normal loudness variations of speech sounds for implant listeners.

METHODS

Eight implant users with Ineraid devices participated in this study. They were five men and three women from 40s to 60s in age. All subjects had previous experience in psychophysical experiments and some training was provided for the familiarity of the specific tasks prior to formal data collection. The Ineraid device features a percutaneous plug interface that allows direct access to the intracochlear electrodes and precise control of electric stimulation. Monopolar stimulation of the most apical electrode was used for all subjects in this study.

All sinusoidal and modulated stimuli were generated digitally and played through a 12-bit digital to analog converter at a sampling rate of 20 kHz (Data Translation DT2801-A). Stimuli included simple sinusoids with frequencies of 100 Hz and 1,000 Hz, and complex stimuli consisting of a 1,000-Hz sinusoidal carrier modulated in amplitude by a 100-Hz sinusoid with a modulation depth of 50% or 100%. All stimuli were 300 milliseconds (ms) in duration and had a linear ramp of 10 ms. The digital stimuli were smoothed by an anti-aliasing filter at a 5-kHz cutoff frequency and delivered to patients through an optically isolated current source. A safety cutoff switch was used to allow a rapid disconnection from the experimental setup in case of experimenter error or hardware failure that might cause loud or unpleasant stimulation.

The dynamic range was defined as the difference in microamperes between the absolute threshold and the uncomfortable loudness level. The dynamic range data of the 100-Hz and the 1,000-Hz sinusoids for the eight subjects were given in note 10 of Zeng and Shannon.[6] Stimuli were generated and varied in amplitude to cover the entire dynamic range. In the first experiment, a stimulus was presented in a burst fashion with a 300-ms on period and a 500-ms off period. The subject listened to this burst stimulus as long as desired and was required to give a numeric estimate of the loudness of the stimulus. Stimuli of different amplitudes were presented in a random order, and three to five presentations were used to obtain the average estimate for each stimulus.

In the second experiment, a bracketing technique was used to obtain the loudness balance function between the modulated comparison stimuli and the 1,000-Hz sinusoidal standard. Four of the eight subjects participated in this experiment. The subject first listened to the pulsed standard stimulus, and then, by pointing on a touch-sensitive tablet, the subject would control the amplitude of a comparison stimulus alternating with the standard. The subject was instructed to make the comparison stimulus first louder, then softer, and finally equally as loud as the standard. Three to five such measures were repeated for each condition. The subject received no feedback in either the first experiment or the second experiment.

RESULTS

Experiment 1. Figure 1 shows the average loudness estimate (y-axis) as a function of the normalized electric amplitude (x-axis). The normalized amplitude was defined as percentage of dynamic range: (electric amplitude − threshold)/(uncomforable level − threshold). Stimulus amplitude was normalized as percentage of dynamic range (x-axis) so data could be averaged across subjects. The left panel shows loudness function for the 100-Hz sinusoid, and the right panel shows the same function for the 1,000-Hz sinusoid. All data points are the arithmetic mean of the eight subjects, and the error bar on each data point represents 1 SD across subjects. The solid lines represent the prediction of the best fit functions, displayed in the bottom right corner of each panel.

Consistent with prediction of our previous work,[6] the present results show that loudness growth for the 100-Hz sinusoid can be described by a power function with an exponent of 0.67 (left panel), whereas loudness growth for the 1,000-Hz sinusoid can be best described by an exponential function (right panel). Attempts were also made to fit an exponential function to the 100-Hz data and a power function to the 1,000-Hz data, but this resulted in a poorer fit.

Experiment 2. Figure 2 shows the loudness balance results for four individual implant subjects. The x-axis represents the amplitude in microamperes for the 1,000-Hz sinusoidal standard, whereas the y-axis represents the amplitude for the 1,000-Hz carrier (not overall modulated stimulus amplitude). The open triangles on each panel represent a control condition (modulation depth = 0%) where the standard and the comparison were the same 1,000-Hz sinusoid. In the panels of subjects JP and MK, note the small deviation of the measured data from perfect matches (dashed diagonal lines). This control condition demonstrates good reliability of the present loudness balance technique. Control data were not collected for the subjects BO and JB, so theoretically perfect matches are indicated by stars. The open circles and the solid squares represent loudness balance data for the 50% and 100% modulated stimuli, respectively. The solid lines represent the prediction of best fits using a linear function.

The most important result of the present study is that all loudness balance data, independent of modulation depth, can be best described as a linear function of the 1,000-Hz standard amplitude. This finding indicates that loudness for modulated stimuli is an exponential function of the electric amplitude. In other words, the modulated stimuli, despite the low-frequency envelope, have the same underlying loudness function as the high-frequency carrier.

A final interesting note in Fig 2 is that although each loudness balance function is linear, its slope decreases as the modulation depth increases. At low levels, a similar carrier amplitude was needed to balance the standard loudness for all three modulation depth conditions; but at high levels, smaller carrier amplitude was needed for stimuli of greater modulation depth for equal loudness. For example, in the 100% modulation condition for subject MK (solid squares in the bottom-right panel), a carrier amplitude of 33.3 μA for the 100% modulated stimulus was required to balance the loudness of a standard amplitude of 35.0 μA, but a carrier amplitude of only 69 μA was required to balance the loudness of a standard amplitude of 135 μA. This pattern of data suggests that loudness of modulated stimuli is determined by two different mechanisms at low and high sensation levels. A model that is under investigation uses a root mean square (RMS) amplitude to predict loudness at low levels and a peak amplitude at high levels.

DISCUSSION

Relation to Previous Studies. Loudness of simple stimuli such as sinusoids and pulses has been measured extensively in cochlear implant subjects. Many studies reported a long "tail" for the loudness growth function at low stimulus levels.[8-10] To a great extent, this long tail is an artifact of the use of a logarithmic (or decibel) scale for the stimulus amplitude, which expands the lower portion of the dynamic range while compressing the higher portion. If a linear scale is used, as in Fig 1, then the long "tail" is shortened. Whether a logarithmic or a linear scale should be used depends on stimulus frequency: Zeng and Shannon[6] propose a logarithmic scale for stimuli of low frequencies (<300 Hz) and a linear scale for high frequencies (>300 Hz).

Zeng and Shannon[6] suggested that the power loudness function of low-frequency stimuli may be related to the temporal periodicity. All four subjects in the second experiment reported that both the 50% and 100% modulated stimuli had a low-frequency pitch similar to the 100-Hz modulator. However, the loudness of the modulated stimuli is an exponential function of the stimulus amplitude despite the low-frequency pitch. It appears that our previous model needs to be extended or modified to accommodate the new data.

Relation to Speech Processor Design. One of the most important considerations in speech processor design for implant users is the necessity to compress the acoustic amplitude to a much narrower range for electric stimulation. An ideal compression would map a value in acoustic amplitude into a value in electric amplitude so that the loudness is the same between two stimulation methods. The present results show that the low-frequency envelope has no effect on the form of loudness growth for the modulated stimuli, which is an exponential function similar to that of the high-frequency carrier. This result means that a logarithmic mapping function[4] is appropriate in a continuous interleaved sampling processor[7] or any other processor in which the low-frequency speech envelope modulates a high-frequency carrier.

CONCLUSIONS

In the first experiment, loudness growth was measured by means of magnitude estimation for the 100-Hz and the 1,000-Hz sinusoidal stimuli. The new data are consistent with the prediction by our previous work that the loudness of the 100-Hz sinusoid is a power function of electric amplitude and the loudness of the 1,000-Hz sinusoid is an exponential function. In the second experiment, the loudness balance data obtained by using a 100-Hz sinusoid to amplitude-modulate a 1,000-Hz sinusoid indicate that the loudness of modulated stimuli follows the same loudness function as the high-frequency carrier, despite the low-frequency pitch perception.

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