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Power functions of loudness magnitude estimations and auditory brainstem evoked responses

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The correspondence between subjective and neural response to change in acoustic intensity was considered by deriving power functions from subjective loudness estimations and from the amplitude and latency of auditory brainstem evoked response components (BER). Thirty-six subjects provided loudness magnitude estimations of 2-sec trains of positive polarity click stimuli, 20/sec, at intensity levels ranging from 55 to 90 dB in 5-dB steps. The loudness power function yielded an exponent of .48. With longer trains of the same click stimuli, the exponents of BER latency measures ranged from −.14 for wave I to −.03 for later waves. The exponents of BER amplitude-intensity functions ranged from .40 to .19. Although these exponents tended to be larger than exponents previously reported, they were all lower than the exponent derived from the subjective loudness estimates, and a clear correspondence between the exponents of the loudness and BER component intensity functions was not found.

For many sensory dimensions, Stevens's power law has been an appropriate model for describing the relationship between stimulus energy change and sensory experience (S. S. Stevens, 1961). The successful application of the power law to psychophysical functions has encouraged speculation on the question of whether changes in evoked potential activity which are contingent on changes in stimulus intensity can be described by power functions with exponents similar to those obtained in psychophysical studies (S. S. Stevens, 1970, 1971). Within the auditory modality, there is some evidence to suggest that the growth in amplitude of the late (80-350 msec) components of the auditory averaged evoked response with increases in stimulus intensity can be adequately described by power functions (Botte, Bujas, & Chocolle, 1975; Davis, Bowers, & Hirsh, 1967; Davis & Zerlin, 1966; Keidel & Spreng, 1965; Walsh, 1979). Power functions have also been derived for the midlatency (15-80 msec) components (Madell & Goldstein, 1972). It has generally been found, however, that the exponents for these functions are lower than those derived from subjective loudness estimations for the same subjects.

In contrast to these reports, Pratt and Sohmer (1977) obtained exponents of .27 and .29 for the amplitude-intensity function of the first two positive waves in the early (0-10 msec) auditory brainstem evoked response (BER) that were comparable to an exponent of .26 derived from concurrent loudness estimations of single-click stimuli. That this correspondence was obtained with the earliest components of the BER would seem to agree with S. S. Stevens (1970) suggestion that the power law applies at the receptor level. The auditory nerve and the cochlear nucleus have been tentatively identified as the neural generators of these first two components, while the superior olivary complex, the nucleus of the lateral lemniscus and the inferior colliculus have been implicated as primary determinants of the subsequent BER components (Huang & Buchwald, 1977). As Pratt and Sohmer (1977) pointed out, however, the low concordance between the psychophysiological and psychophysical power functions determined for individuals may indicate that the correspondence is, in fact, superficial. Moreover, the exponent derived from the subjective magnitude estimations was considerably lower than those typically reported for loudness functions relative to the sound pressure scale. Raab and Osman (1962), for example, reported an exponent of .49 for the loudness function to click stimuli. Nevertheless, the stability of the observed coincidence warrants further investigation using alternative psychophysical and BER recording procedures.

METHOD

Subjects

Thirty-six women students enrolled in introductory psychology classes served as subjects. The mean age for this sample was 19.3 years (SD = 2.0). None of the participants had had prior experi-

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ence with either psychophysical scaling techniques or evoked response recording procedures. During the data collection, the subjects relaxed in a reclining chair located in a soundproof room adjacent to the equipment room.

Stimuli

The click stimulus was a .1-msec-duration square pulse of positive polarity produced by a Rutherford B14-R pulse generator and amplified by a Lafayette Model 1421 audio amplifier. The stimuli were presented monaurally to the right ear through shielded Belltone earphones at a rate of 20/sec. Intensity levels were controlled by a Hewlett-Packard 4437A attenuator and were calibrated at the earphone by a Bruel and Kjaer Type 2204 sound-level meter (A-weighting) and a Type 4152 artificial ear. The eight intensity levels ranged from 55 to 90 dB SPL in 5-dB steps.

Subjective Loudness Estimations

The signals the subjects rated were short 2-sec trains of clicks at each of the eight intensity levels. A free-modulus direct scaling procedure was employed. In this task, the subject assigned a number to each stimulus in direct proportion to the subjective loudness. No standard stimulus with a reference value was provided, and ratings were not restricted to a specific range of numbers, except that ratings of 0 or negative value were not permitted. The ratios between the perceived magnitude of successive stimuli provided the basis for determining the intensity-loudness function. Two loudness estimates were obtained from each subject at each intensity level. The order of presentation of the intensity levels was random.

BER Recording

The brainstem evoked responses were recorded after the completion of the loudness estimation task. The EEG was recorded with Beckman Ag-AgCl electrodes (11 mm) from the vertex (positive) placement referenced to the right mastoid. The right wrist served as ground. Interelectrode impedance was below 5 kΩ. The EEG signal was amplified 56 dB by a Nihon-Kohden RB-5 biophysical amplifier housed in a Nihon-Kohden RM-85 polygraph. The signal was filtered with a Krohn-Hite 3550 filter set at a bandpass of 100-3,000 Hz and passed to the A/O interface of a Digital PDP-8/e computer. The computer performed on-line averaging at a sampling rate of 512 points/14.6 msec analysis time, initiated at stimulus onset. Two BERs were computed concurrently at each intensity by separately averaging responses to alternate stimuli within a train of 4,096 clicks. The degree of congruence between the two waveforms served as an index of the reliability of recording and as an aid to wave identification. These waveforms were plotted on a Moseley X-Y plotter. Positive waves I, II, III, V, and VI of the BER waveform were labeled following the convention proposed by Jewett and Williston (1971). Wave IV often merged with wave V or was difficult to discern in the background noise. For this reason, it was not quantified. The five negative waves (N1, N2, N3, N5, N6) preceding the positive peaks were also analyzed. The latency and amplitude of each wave were independently determined for each of the concurrently recorded waveforms and then averaged to provide a single latency and amplitude value for each wave. The wave amplitude was obtained by measuring from the apex of the wave to the subsequent negative trough for each positive wave and to the preceding positive peak for each negative wave. The waveforms obtained from a typical subject are shown in Figure 1.

Data Reduction

The free-modulus loudness estimation task requires the removal of the effects of intersubject variability in the choice of the modulus. This was achieved by calculating a constant for every subject based on the deviation of the subject's average log estimate from the mean of the log estimates (Engen, 1971). Correction of the individual log estimates with these constants resulted in a matrix of transformed log responses in which variability due to modulus choice was minimized. The exponents of the power functions were derived by determining the least squares regression of the transformed log loudness estimates on intensity levels. Exponents were calculated for the sample and for each individual. The same calculations were applied to the latency and amplitude measures to obtain exponents for the intensity-BER function of each BER component.

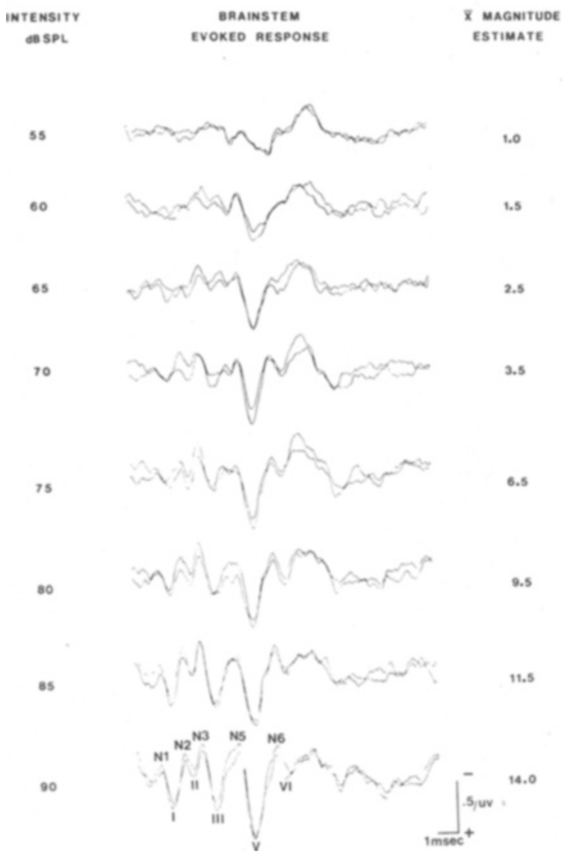

Figure 1. Results obtained from one subject. Each tracing represents the average of responses to 2,048 clicks. Positive at the vertex is a downward deflection.

RESULTS

For several subjects under the higher intensity conditions, wave N2 appeared in a fused form with the initial negative rise of wave N3. In those cases, wave N2 measures were not obtained and were not included in the computation of group exponents. Specifically, one subject at 55, 80, and 85 dB and five at 90 dB were excluded from the analysis of wave N2. The amplitudes of waves VI and N6 were not scoreable for one subject at 65, 80, 85, and 90 dB.

The latency and amplitude of the BER waves observed in the present study are in good agreement with values previously reported for similar intensity levels under similar recording conditions (cf. Rowe, 1978; Salamy, McKean, Pettett, & Mendelson, 1978; Starr & Achor, 1975). The mean and standard deviation for the latency and amplitude of each positive-

Table 1
Mean Latency (in Milliseconds) and Amplitude (in Microvolts) of Vertex Positive BER Waves for Each Intensity Level (N = 36)

	Brainstem Component									
	I		II		III		V		VI	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
					55 dB SPL					
Latency	2.60	.31	3.51	.33	4.77	.45	6.97	.41	8.49	.58
Amplitude	.08	.05	.11	.05	.13	.07	.31	.10	.13	.08
					60 dB SPL					
Latency	2.39	.31	3.29	.33	4.52	.47	6.78	.41	8.35	.50
Amplitude	.09	.05	.12	.05	.13	.08	.32	.11	.14	.09
					65 dB SPL					
Latency	2.19	.30	3.14	.30	4.44	.45	6.53	.41	8.08	.60
Amplitude	.11	.09	.15	.05	.14	.17	.30	.12	.17	.10
					70 dB SPL					
Latency	2.07	.24	3.05	.26	4.27	.40	6.41	.38	7.84	.47
Amplitude	.12	.06	.18	.06	.13	.06	.32	.12	.19	.11
					75 dB SPL					
Latency	1.99	.24	2.96	.25	4.19	.33	6.23	.33	7.69	.44
Amplitude	.13	.06	.20	.07	.18	.09	.34	.14	.23	.12
					80 dB SPL					
Latency	1.91	.16	2.89	.20	4.10	.27	6.09	.26	7.74	.40
Amplitude	.17	.08	.24	.07	.23	.13	.46	.15	.22	.10
					85 dB SPL					
Latency	1.83	.17	2.84	.21	4.04	.28	5.98	.26	7.76	.35
Amplitude	.26	.09	.26	.09	.31	.17	.56	.16	.28	.12
					90 dB SPL					
Latency	1.73	.14	2.80	.20	3.94	.26	5.95	.33	7.66	.36
Amplitude	.34	.09	.31	.13	.31	.19	.58	.17	.29	.22

wave component of the BER are shown in Table 1. The latency of the BER components decreased as stimulus intensity was increased and yielded negatively accelerated power functions. The exponents obtained for the latency values of positive waves were: wave I, −.09 (SD = .03); wave II, −.05 (SD = .02); wave III, −.04 (SD = .02); wave V, −.04 (SD = .02); wave VI, −.03 (SD = .02). The exponents obtained for the latency values of negative waves were: N1, −.14 (SD = .03); N2, −.09 (SD = .06); N3, −.06 (SD = .02); N5, −.04 (SD = .02); N6, −.03, (SD = .06).

The amplitudes of the BER components generally increased as stimulus intensity increased and yielded positive power functions. The exponents derived for the amplitude values of positive waves were: wave I, .40 (SD = .15); wave II, .28 (SD = .14); wave III, .25 (SD = .21); wave V, .19 (SD = .09); wave VI, .23 (SD = .21). The exponents obtained from the amplitudes of the negative peaks were: N1, .37 (SD = .12); N2, .30 (SD = .22); N3, .38 (SD = .17); N5, .22 (SD = .09); N6, .23 (SD = .21).

The subjective loudness magnitude estimations yielded an exponent of .48 (SD = .14). In general, then, the exponents derived from the amplitude values resemble the loudness power function more closely than exponents derived from the latency values. The largest exponents from the BER amplitude components were from positive wave I and from negative waves 1 and 3, but these exponents were smaller than the exponent of the intensity-loudness function.

The best-fit regression lines plotted for the loudness estimations and for the amplitudes of each negative wave component as a function of intensity are shown in Figure 2. According to the power law proposed by S. S. Stevens (1961), the plot of response magnitude against intensity in double logarithmic coordinates is a straight line. Inspection of Figure 2 shows that the relationship of these BER amplitudes to intensity levels is not precisely linear. Specifically, the BER amplitude-intensity functions tend to depart from linearity at the lower intensities. As a first approximation, however, power functions described the data very well. Linear trend components computed from the log amplitude measures of these negative waves, for example, account for more than 92% of the variance across intensity levels for each wave (N1, 96%; N2, 93%; N3, 97%; N5, 97%; and N6, 93%).

The extent of agreement between the subjective

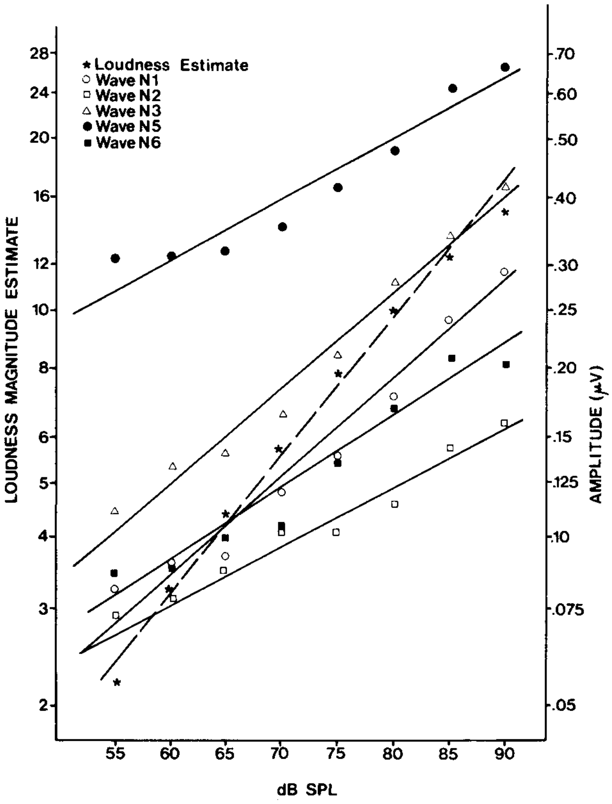

Figure 2. Loudness magnitude estimations and BER amplitudes of negative waves plotted as power functions of stimulus intensity.

loudness and BER intensity functions was explored by employing the BER exponents as predictors in a stepwise multiple regression analysis. Correlation coefficients based on the loudness exponent for each subject and their corresponding BER latency and amplitude exponents were low and not significant in all cases. As indicated by the coefficient of determination, r^2, in three dependent analyses, the exponents of the amplitude measures and of the latency of positive waves accounted for less than 10% of the variance of the loudness exponent. The conjoint influence of the exponents of the latency of negative waves accounted for 54% of the variance in the loudness exponents, but this effect was determined primarily by a relatively high correlation between the loudness exponent and wave N2, $r = .33$, which was opposite to the predicted direction, and, consequently, the effect must be regarded as spuriously large. Overall, there is little evidence of concordance between the loudness and BER components in this analysis.

DISCUSSION

The exponent of .48 obtained for the loudness estimations concurs very well with the reference value of .49 for click stimuli given by Raab and Osman (1962). As Pratt and Sohmer (1977) observed, the loudness exponent was more closely approximated by the exponents of intensity-amplitude functions than by exponents of intensity-latency functions. With the exception of wave II, the exponents of the intensity-amplitude functions for the auditory nerve and BER components were larger than have been previously reported (Pratt & Sohmer, 1977). For all BER components, however, the exponents were smaller than the value obtained for the intensity-loudness function. This finding is consistent with similar comparisons for exponents of intensity functions of late and midlatency evoked potential components (Botte, Bujas, & Chocolle, 1975; Davis & Zerlin, 1966; Keidel & Spreng, 1965; Madell & Goldstein, 1972; Walsh, 1979).

The disparity between the BER and loudness exponents observed in the present study and those reported by Pratt and Sohmer (1977) appear to depend primarily on differences in stimulus presentation procedures. With regard to the loudness exponents, the higher value obtained here was derived from the scaling of trains of click stimuli rather than individual clicks. Raab and Osman (1962) have suggested that low exponents may be obtained to ratings of individual click stimuli due to the brevity of the acoustic transient. Although decreasing stimulus duration has not been shown to affect the slope of the loudness function (J. C. Stevens & Hall, 1966), the use of extremely short durations may make the magnitude scaling a more difficult task, a complication that tends to result in lower exponents. The BERs obtained in the present experiment were recorded in response to clicks presented in a long train at the same rate as for the psychophysical task. Given the similarity of these conditions, it seems likely that the actual perceived loudness during the evoked response recording session was, in fact, well approximated by the method of stimulus presentation employed for the magnitude estimations, and that the higher exponent therefore provides an appropriate comparison.

For the range of intensities employed, the power law describes the intensity-amplitude function for BER components very well. There were clear differences, however, between the exponents derived from the psychophysical and psychophysiological methods, with the intensity-subjective loudness function showing faster growth than the intensity-BER functions. These differences were underscored in the analysis of exponents calculated for individual subjects. Very little concordance between the exponents of subjective loudness and BER amplitude intensity functions was evident in the regression analysis. Since the individual slopes of the loudness estimates were based on only two judgments for each intensity level, the reliability of the exponents and the appropriateness of the individual analysis may be open to some question. The extent of individual variation for the loudness exponents, however, was quite similar to that obtained for the BER exponents, and the same degree of reliability would seem to apply in this case. It should also be noted that for intensity levels below 60 dB, amplitude values were not appreciably different, or leveled off, and the slope of the intensity amplitude function would tend to be lower than the slope of the monotonically increasing amplitude values above 60 dB.

In conclusion, the present evidence can be taken to indicate that, although the power function describing the growth in the subjective experience of loudness with increases in sound pressure is approximated by the power function describing the increases with the amplitude of early auditory brainstem evoked responses, clear evidence of their mutual dependence was not found. The brainstem potentials recorded with far-field techniques may be the consequence of a number of neural actions, including the differential action of simultaneous activity in multiple generators and sustained activity in single generators, as a number of authors have suggested (cf. Stockard, Stockard, & Sharbrough, 1978). That is to say, the BER components may serve as codes rather than signs of auditory experience. Such effects would attenuate the concordance of the loudness and BER intensity functions. Alternatively, the loudness power function may be determined by more complex neural interactions that are not adequately considered with the present evoked potential measures.

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