COMBINED EFFECTS OF RECOVERY PERIOD AND STIMULUS INTENSITY ON THE HUMAN AUDITORY EVOKED VERTEX RESPONSE

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Averaged auditory evoked vertex responses were obtained from eight normal-hearing subjects in response to 32 monaural 1000-Hz tone bursts at 30 combinations of recovery period and stimulus intensity. From curves describing N_1-P_2 peak-to-peak amplitudes, an equation was derived that describes the combined effects of recovery period and stimulus intensity on evoked response amplitude. The results show evoked response amplitude to be a dual function of both recovery period and stimulus intensity. At a given stimulus intensity, evoked response amplitude increases as a logarithmic function of recovery period. At a given recovery period, evoked response amplitude increases as a power function of stimulus intensity. The combined effects of recovery period and stimulus intensity produce equal ratio changes in the slope of the recovery function with equal ratio changes in stimulus intensity.

Several stimulus variables, such as intensity, duration, rise-time, frequency, and recovery period, influence the late auditory evoked vertex response. Of these, intensity and recovery period are the most influential.

Many investigators have explored the effects of stimulus intensity on the auditory evoked vertex response (Antinoro, Skinner, and Jones, 1969; Butler, Keidel, and Spreng, 1969; Davis and Zerlin, 1966; Keidel and Spreng, 1965b; Rapin et al., 1966). All show that magnitude of the evoked vertex response increases with increasing stimulus intensity, and that latency of the evoked vertex response decreases with increasing stimulus intensity.

The effects of recovery period on the auditory evoked vertex response have received less quantitative attention (Keidel and Spreng, 1965a, b; Davis et al., 1966; Davis and Zerlin, 1966; Nelson and Lassman, 1968), but it seems clear that recovery period is a parameter that produces both large and consistent changes in the evoked vertex response. Nelson and Lassman (1968) determined that the magnitude of the evoked vertex response was a linear function of the logarithm of the recovery period. For every tenfold increase in recovery period, they found a 5.6 microvolt increase in evoked vertex response magnitude (N_1-P_2 peak-to-peak amplitude). This relation was found to hold true for recovery periods from 0.5 seconds up to 10 seconds. Other data from this laboratory and from Keidel and Spreng's (1965b) study suggest that further increases in amplitude of the evoked vertex response may occur with increases in recovery periods up to about 30 seconds.

Keidel and Spreng (1965a) presented results suggesting an interaction between the effects of stimulus intensity and recovery period. They found steeper intensity functions (amplitude of the evoked vertex response growth with stimulus intensity) for evoked vertex responses obtained with a 30-second recovery period than with a one- to three-second recovery period. Further support for this notion can be gained by comparing a recovery function (amplitude growth with recovery period) obtained by Davis and Zerlin (1966) at 85 dB hearing level (HL) with a recovery function obtained by Nelson and Lassman (1968) using a 60 dB sensation level (SL) stimulus. The recovery function for the 85 dB HL (probably 75-80 dB SL) stimulus was steeper than the one reported for the 60 dB SL stimulus. There were methodological differences in addition to stimulus level differences between those two studies, yet when the results of the comparison between those two studies of recovery period are combined with the results of Keidel and Spreng (1965a), the suggestion is clear that an interaction between the effects of stimulus intensity and the effects of recovery period on the evoked vertex response may exist. These studies clearly imply that higher stimulus levels produce steeper recovery functions; stated differently, longer recovery periods may produce steeper intensity functions.

The purpose of the experiment reported in this paper was to quantitatively examine the combined effects of intensity and recovery period on the auditory evoked vertex response. Two questions were asked: Is there an interaction between the effects of stimulus intensity and the effects of recovery period? If there is an interaction, what is the nature or form of that interaction?

METHOD

Experimental Design

Since the primary purpose of this investigation was to examine the combined effects of both stimulus intensity and recovery period on the evoked vertex response, an experimental design that would permit an examination of either variable (recovery period or stimulus intensity) independently from the other was used. Five recovery periods (0.5, 1.0, 2.0, 4.0, and 8.0 seconds between signal onsets, that is, the inverse of repetition rate) and six stimulus intensities (15, 30, 45, 60, 75, and 90 dB sensation level) were chosen to represent the two independent variables. In addition, two types of control conditions were presented at each of the five recovery periods. One control condition was an averaged evoked response obtained by addition and subtraction of alternate evoked responses to a 60 dB SL tone burst, which was intended to estimate electroencephalic "noise" level during stimulation. The other control condition was a "no-stimulus" average of the electroencephalic activity, intended to estimate the "noise" level during quiet. These two control conditions, plus the six stimulus intensities and the five recovery periods, yielded a $(2 + 6) \times 5$ or an 8×5 matrix of conditions consisting of 30 combinations of recovery period and stimulus intensity and 10 control conditions. For each subject, the order in which the 40 conditions were presented was randomly selected.

Recording sessions were limited to approximately one hour to minimize subject fatigue. Of the 40 conditions, 10 were presented during a single session. Following each condition, a short silent interval of one to two minutes was maintained, and a five-minute "rest break" was allowed halfway through each experimental session.

Subjects and Subject-State

Experimental subjects were eight female volunteers with "normal hearing" (thresholds for the 18-msec 1000-Hz tone bursts below 20 dB SPL) and with no history of an abnormal EEG. Their ages ranged from 20 to 25 years. During recording of evoked responses, each subject reclined in a lounge chair, with her head resting against the back of the chair, reading fictional material of her choice. A subject-state of reading was chosen to minimize "waxing and waning" of attention toward the acoustic events. Reduced variance between and within subjects during reading as compared to counting, as shown by Gross et al. (1965), supports the choice of subject-state used in the present study.

Stimulus Parameters

The acoustic events used to obtain an evoked response were 1000-Hz tone bursts triggered at the zero-crossing of a 1000-Hz tone. The duration of the tone bursts, measured at 90% of maximum peak amplitude, was 18 msec, and the rise and the fall times, measured between 10 and 90% of maximum peak amplitude, were each 18 msec. The tone bursts were delivered to each subject's right ear through an earphone (Type TDH 39) mounted in a circumaural muff (Maico Auraldome).

Each subject's threshold for the 1000-Hz tone bursts was measured in 2-dB steps with a descending method of limits. This was done after the electrodes had been placed on the scalp and after all preparations had been made for an experimental run. Stimulation intensities were then referred to that threshold and are therefore specified in dB sensation level (SL).

Electroencephalographic Recording

To record electroencephalic activity, three electrodes (Grass Silver-cup) were placed on the scalp and attached with electrode cream (Grass Type EC-2) and surgical tape. An active electrode was placed at the vertex, a reference electrode on the left mastoid or left earlobe, and a ground electrode on the left forehead. The electroencephalic activity was amplified by a differential amplifier (Tektronix, Model 2A61) and then filtered with a 0.6-60 Hz bandpass filter and a 60 Hz rejection filter. It was then routed directly to the signal averager.

Electrical noise throughout this system, with 10-k Ohm resistors across the input instead of a subject's scalp, was estimated with the aid of an oscilloscope (Tektronix, Model 565) to be less than 2.0 microvolts.

Averaging and Measurement of Auditory Evoked Responses

A signal averager (Fabri-Tek, Model FT1052) with its associated amplifier (Fabri-Tek, Model FT100) was used to average the 32 epochs of electroencephalic activity that made up each averaged evoked response. The signal averager digitized a 512-msec segment of the filtered electroencephalic activity following the onset of each acoustic stimulus and stored those digitized segments in its memory. In effect, the signal averager digitized the electroencephalic activity into 256 addresses (2 msec per address), so the resulting summed response was represented by 256 addresses in the computer's memory.

The averaged evoked vertex responses were traced from the computer memory onto graph paper with an *X-Y* plotter (Moseley, Model 1035A). Seven measures were made of each averaged evoked response: P_1 peak latency (40-90 msec), N_1 peak latency (90-175 msec), P_2 peak latency (175-300 msec), P_1-N_1 peak-to-peak amplitude, N_1-P_2 peak-to-peak amplitude, and P_2-N_2 peak-to-peak amplitude (conventions of waveform specification similar to Davis, 1965). Since the graphic display of the averaged evoked vertex response was calibrated into 20 divisions for every 100 msec, the resolving power of the latency measures was 5 msec. The *X-Y* plotter was calibrated at 0.4 microvolts per division, therefore measurements of response amplitude were made to the nearest 0.4 microvolts.

A single averaged evoked vertex response in this investigation was the average of 32 512-msec segments of electroencephalic activity, 50 msec preceding and 462 msec following the onset (10% of maximum peak amplitude) of each tone burst. Forty averaged evoked vertex responses were obtained from each subject, one for each of the 40 combinations of experimental conditions. However, since there were no consistent differences among control conditions and the control conditions did not exhibit averaging artifacts, only the averaged evoked responses that involved the 30 combinations of six stimulus intensities and five recovery periods will be dealt with in the data analysis.

RESULTS AND DISCUSSION

Recovery-Period Effects on Evoked Response Amplitude

Mean evoked vertex response peak-to-peak amplitudes of the various components are shown in Figure 1 as a function of recovery period. Sensation level of the tone bursts is the parameter. The combined effects of recovery period and of stimulus intensity are obvious in these data. Amplitude of the evoked

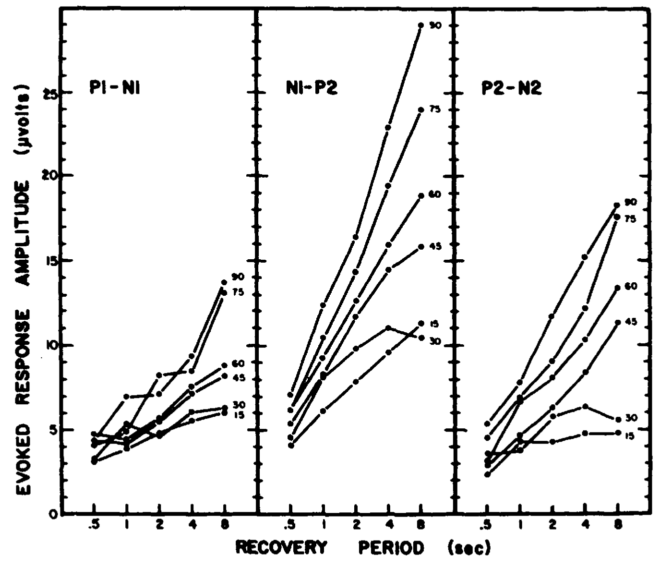

FIGURE 1. Recovery functions of amplitude of the evoked vertex response by sensation level for each of the three peak-to-peak amplitude measures: P_1-N_1, N_1-P_2, and P_2-N_2. Each evoked vertex response was based upon responses to 32 1000-Hz tone bursts. Each data point is the mean across eight normal-hearing subjects.

vertex response is dependent on both recovery period and stimulus intensity. The non-parallel recovery functions demonstrate that there is an interaction between the effects of intensity and recovery period on the auditory evoked vertex response. The second question as to the nature of this interaction can now be dealt with.

The recovery functions for the N_1-P_2 amplitudes shown in Figure 1 can be adequately described by logarithmic functions, that is, for every constant ratio increase in recovery period (Rp), a constant microvolt increase in evoked response amplitude (ϕ) results. The form of this function is given in Equation 1:

$$\phi = k + n\,(\log_{10} Rp) \qquad (1)$$

where k is the intercept and n is the slope of the logarithmic recovery function. These results and Equation 1 are in complete agreement with the results of Nelson and Lassman (1968) for N_1-P_2 recovery functions obtained at a single sensation level (60 dB).

The effects of stimulus intensity on evoked vertex response recovery functions can be simply stated. Higher stimulus intensities produce larger amplitudes and steeper recovery functions; stimulus intensity has more effect on evoked vertex response amplitude at long than at short recovery periods; the effect of recovery period is greater at high than at low sensation levels. These statements about the combined effects of recovery period and stimulus intensity on amplitude of the evoked vertex response can be described with an equation, but first the nature of intensity functions should be considered.

Stimulus-Intensity Effects on Evoked Response Amplitude

The mean peak-to-peak amplitude measures of the evoked vertex response are replotted logarithmically as a function of sensation level (also logarithmic scale) in Figure 2. Such linear functions plotted on log-log coordinates are called power functions (Stevens, 1961). They will be referred to in this paper as intensity functions, that is, evoked vertex response amplitude as a function of stimulus intensity.

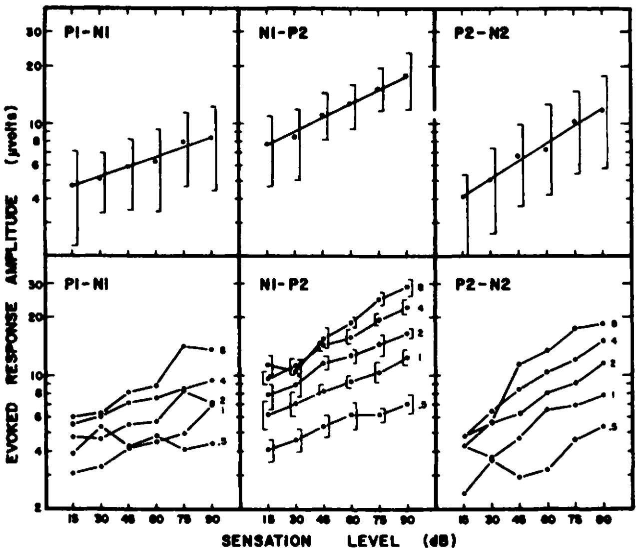

FIGURE 2. Intensity functions for amplitude of the evoked vertex response. The top three sections contain the intensity functions averaged across recovery periods in order to show the relations among the three amplitude measures. The vertical bars in the top three sections are pooled estimates of one standard deviation either side of the mean. The bottom three sections contain the intensity functions by recovery period. The vertical bars in the bottom center section are pooled estimates of one standard error either side of the mean.

The upper three sections of Figure 2 contain plots of the amplitude data of the evoked vertex response, averaged across recovery periods, and are intended to show the form of the intensity function for each of the three different peak-to-peak amplitude measures. All three intensity functions can be described as power functions, relating magnitude of the evoked vertex response to physical stimulus. That is, for every constant ratio increase in stimulus intensity (I), a constant ratio increase in the amplitude of the evoked vertex response (ϕ) results. The form of this function is given in Equation 2, where I represents stimulus intensity, I_0 is a value corresponding to "threshold" intensity, k is a constant describing the intercept of the intensity function, and n is the exponent (slope) of the intensity function:

$$\phi = k\,(I-I_0)^n \tag{2}$$

The bottom three sections of Figure 2 contain the intensity functions with recovery period as the parameter. The N_1-P_2 components are larger and show less relative variance than either the P_1-N_1 or the P_2-N_2 components. The nature of the combined effects of recovery period and stimulus intensity can again be described, this time in terms of intensity functions: longer recovery periods produce larger absolute amplitudes (k) and steeper slopes (n) in evoked vertex response intensity functions.

Combined Effects of Recovery Period and Stimulus Intensity

Since the N_1-P_2 amplitude measure is the largest of the three amplitude measures (Figures 1 and 2), this measure was used to search for a set of curves that would adequately describe the combined effects of recovery period and stimulus intensity. Initially, straight-line curves were visually fit to the N_1-P_2 amplitude data when plotted as recovery functions with sensation level as the parameter. Those visually fit curves were then transferred to a new graph on which the N_1-P_2 amplitude data were replotted as intensity functions with recovery period as the parameter. Those straight-line intensity-function curves were then readjusted slightly in slope and intercept to visually fit the N_1-P_2 amplitude data plotted as intensity functions. This process of visually fitting the N_1-P_2 amplitude data when plotted as recovery functions and then readjusting the curves when plotted as intensity functions was repeated twice to obtain the set of derived curves shown in Figures 3 and 4.

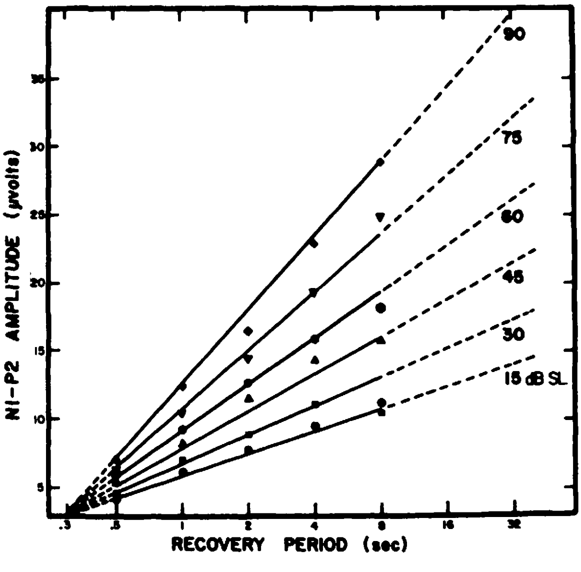

FIGURE 3. Derived recovery curves for N_1-P_2 peak-to-peak amplitude. The straight-line curves were visually fit to the N_1-P_2 mean amplitudes plotted either as recovery functions or as intensity functions (see text). The curves can be described with the same derived data points that are used in Figure 4 to fit the data when plotted as intensity functions. The dashed lines are extrapolations.

Both figures contain the same N_1-P_2 amplitude data and the same set of visually fit curves. Those derived curves are based on two assumptions: (1) that the recovery functions are logarithmic functions, and (2) that the intensity functions are power functions. The N_1-P_2 peak-to-peak amplitude data and data points describing the derived curves are given in Nelson's (1970) appendix.

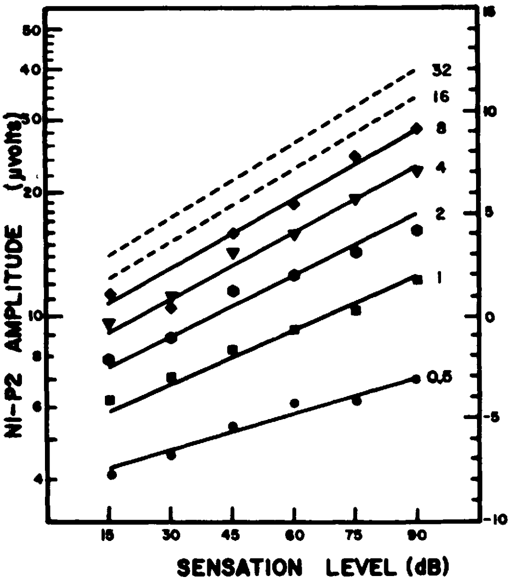

FIGURE 4. Derived intensity functions for N_1-P_2 peak-to-peak amplitude. The straight-line curves were visually fit to the N_1-P_2 mean amplitudes plotted either as intensity functions or as recovery functions. The curves can be described with the same derived data points that are shown in Figure 3 to fit the data when plotted as recovery curves. The dashed lines are extrapolations.

Figure 3 contains the derived curves and the original mean N_1-P_2 amplitudes, both plotted as recovery functions. Sensation level is the parameter. Those derived recovery curves follow Equation 1. The dotted lines in Figure 3 are extrapolations to shorter and longer recovery periods than were actually employed in this study. Extrapolations to longer recovery periods seemed justifiable in view of data from Keidel and Spreng (1965a) suggesting that evoked vertex response amplitude continues to increase as recovery period is increased up to 30 seconds. Also, unpublished data in our laboratory show increasing amplitudes of the evoked vertex response from recovery periods of nine to 24 seconds, and even up to 54 seconds.

The extrapolations toward shorter recovery periods are largely hypothetical, even though Rau (1968) as well as Nelson and Lassman (1968) reported decrements in amplitude of the evoked vertex response for recovery periods down to 0.25 seconds. Responses obtained with recovery periods shorter than 0.25 seconds are likely to be affected grossly by the N_2 and the even later P_3 peak components of previous responses. For example, when only about 200 msec separate two consecutive acoustic stimuli, the P_3 component of the response to the first stimulus will occur at about the same time as the N_1 component of the response to the second stimulus. Cancellation will take place between P_3 and N_1 because the two components are of opposite polarity.

Figure 4 contains the same set of derived curves and the original mean N_1-P_2 amplitudes; this time both are plotted as intensity functions with recovery period the parameter. The straight-line functions follow Equation 2; that is, the data are fit with power functions. The steepness of those intensity functions varies with the parameter (recovery period) as evidenced by the exponents (n) of Equation 2. Those exponents vary from 0.06 for the 0.5-

second recovery period to 0.112 for the eight-second recovery period. The dashed lines show the extrapolated data from the recovery functions in Figure 3, thereby estimating the expected intensity functions for recovery periods of 16 and 32 seconds.

The exponents (n) describing the slope of the N_1-P_2 intensity functions are plotted in Figure 5 as a function of recovery period (filled circles). The steepness of the intensity functions does not increase indefinitely with recovery period, but gradually reaches an asymptote. This result is reasonable, since there should be a point where the system reaches an unadapted state, that is, a recovery period during which the response to a previous stimulus no longer has an appreciable effect on the response to a subsequent stimulus.

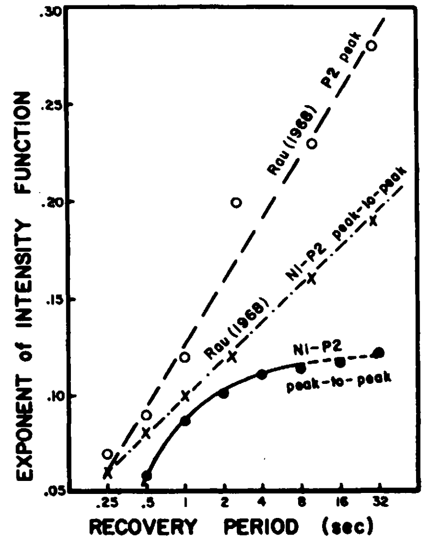

FIGURE 5. Exponents (slopes) of the intensity functions for N_1-P_2 peak-to-peak amplitude as a function of the recovery period are shown as filled circles. The unfilled circles are taken from data published by Rau (1968) using a different measure of evoked vertex response amplitude (essentially a P_2 peak measure). The Xs are the conventional N_1-P_2 measure on Rau's data.

Equation for the Combined Effects of Stimulus Intensity and Recovery Period

A more precise description of the combined effects of recovery period and stimulus intensity on N_1-P_2 amplitude can be developed by starting with Equation 1 for the recovery function for the evoked vertex response. Since the recovery functions in Figure 3 change in a regular manner with each change in stimulus intensity, the combined effects of stimulus intensity and recovery period are expressable in the form of Equation 3, where i represents the parameter of sensation level, k is the intercept, and n is the slope of the function, and R_p represents recovery period:

$$\phi = k_i + n_i\,(\log_{10} R_p) \qquad (3)$$

The combined effects of intensity and recovery period can be described as changes in the intercept (k_i) and the slope (n_i) of the recovery functions that occur with changes in stimulus intensity. Do the slopes and the intercepts of these derived recovery curves vary in a regular manner with sensation level? And if they do, what equation will describe those functions?

First, from the slopes of the recovery functions in Figure 6, showing the slopes of the derived recovery curves plotted logarithmically with sensation level in dB, it is apparent that those slopes change as a power function of stimulus intensity (in this case sensation level). That is, for each constant ratio increase in stimulus intensity, there is a corresponding constant ratio increase in the slope of the derived recovery curves.

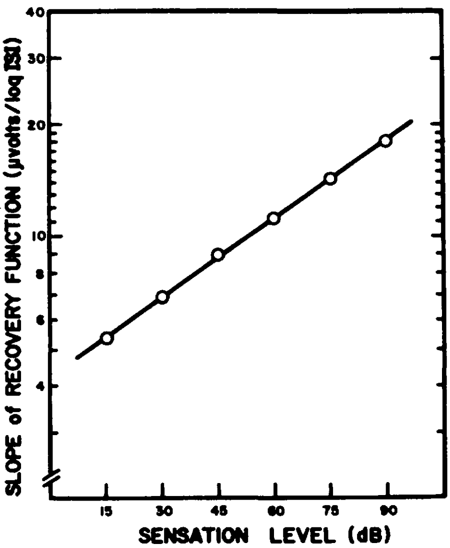

FIGURE 6. Slopes of the recovery curves for N1-P2 peak-to-peak amplitude as a function of sensation level.

Similarly, the intercepts of the derived recovery curves can be plotted logarithmically against sensation level, and a similar power function is obtained. Both the slopes and the intercepts of the recovery functions vary as power functions with sensation level.

An equation can be derived to describe these combined effects by first finding the equation for the slopes (n_i) of the derived recovery curves as a function of stimulus intensity (shown in Figure 6), then finding the equation for the intercepts (k_i) of the derived recovery curves as a function of stimulus intensity, and then finally substituting those equations into Equation 3.

The form of the equation describing changes in the slopes (n_i) of the recovery curves as a function of sensation level is given in Equation 4, where i represents the different sensation levels, b is the intercept and v the slope of the function, I is stimulus intensity, and I_0 is stimulus intensity at threshold:

$$n_i = b_i \, (I\text{-}I_0)^v \qquad (4)$$

The values of the terms in Equation 4 describing the data in the present experiment are $b_i = 4.4$ and $v = 0.1364$.

Using a similar rationale, the form of the equation describing changes in the intercepts (k_i) of the derived recovery curves as a function of sensation level is given in Equation 5, where a is the intercept and w is the slope of the function:

$$k_i = a_i\,(I\text{-}I_o)^w \tag{5}$$

The values of the terms in Equation 5 describing the data in this experiment are $a_i = 8.95$ and $w = 0.1476$.

The combined effects now become describable in the form of Equation 3 by substituting Equation 4 for n_i and Equation 5 for k_i:

$$\phi = a_i\,(I\text{-}I_o)^w + b_i\,(I\text{-}I_o)^v\,[\log_{10} R_p\,(\text{sec})] \tag{6}$$

In essence, Equation 6 implies that for each constant ratio increment in stimulus intensity (sensation level) there is a constant ratio increment in both the slope and the intercept of the N_1-P_2 peak-to-peak amplitude recovery function.

From the data plots comparing the different components of the evoked vertex response in Figures 1 and 2, it can be seen that the P_1-N_2 and P_2-N_2 peak-to-peak measures of amplitude of the evoked vertex response exhibit combined effects of recovery period and stimulus intensity that are similar to N_1-P_2 peak-to-peak amplitude. The data for P_1-N_1 and P_2-N_2 amplitude measures are more variable and do not yield as well to the visual best-fit analysis as do the data for the N_1-P_2 amplitude measure. To a first approximation, however, the form of Equation 6, describing the combined effects of recovery period and stimulus intensity, appears appropriate for all peak-to-peak amplitude measures of the evoked vertex response made in this study.

Equation 6 does not fit Rau's (1968) amplitude measures of the evoked vertex response. Figure 5 shows the exponents (slopes) of the intensity functions that Rau reported. They are plotted with the exponents obtained in this study. Rau's exponents follow an entirely different course as a function of recovery period than do the exponents of this investigation. Both the exponents of her "P_2" peak amplitude measure and the exponents of her N_1-P_2 peak-to-peak amplitude measure are linear functions of the logarithm of recovery period. Her data suggest that the slope (n) of the intensity function continues to increase with recovery period indefinitely. Neither the significance of the differences nor a satisfactory explanation for the differences between the two sets of results is apparent.

ACKNOWLEDGMENT

This research was supported in part by Social and Rehabilitation Services Research and

Training Grant 16-P-56810 and by Public Health Service Grants NB-04403 to the University of Minnesota and NS-04105 to the University of Pittsburgh while the senior author was affiliated with the University of Pittsburgh Bioacoustics Laboratory, Eye and Ear Hospital, and School of Medicine. Requests for reprints should be directed to D. A. Nelson, Department of Otolaryngology, University of Minnesota, Minneapolis, Minnesota 55414.

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Received April 5, 1972.
Accepted January 10, 1973.