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Discrimination of Equal-Energy, Equally Detectable Auditory Stimuli*

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Summary. Two experiments were conducted. In the first experiment, psychometric functions were generated for tones of 988 Hz of 16 and 64 ms duration. The results indicate that for detection, both durations are within critical duration, i.e., equal detection levels were obtained for stimuli of equal energy. In the second experiment, pairs of equal-energy, equally detectable tones of 16 and 64 ms were used to test the ability of subjects to discriminate between them. The results indicate that equal-energy, equally detectable tones of different intensities and durations are discriminable from one another although the durations do not exceed the limits of complete reciprocity when the response measure is detection. Two different interpretations are presented and discussed.

Introduction

Although the integration of stimulus energy for a threshold response appears to be a general phenomenon in all sensory systems, the temporal limits of summation as well as the stimulus parameters determining the extent thereof are unique to each sensory system. Thus, for example, for visual (Rouse, 1952), auditory (Garner and Miller, 1947; Zwislocki, 1960), and mechanical cutaneous stimuli (Verillo, 1965), temporal integration for threshold appears to be total under given stimulus conditions for durations up to 100-200 ms; for electrocutaneous stimuli, on the other hand, only partial temporal integration is reported for durations as short as 0.5 ms (Babkoff et al., 1975; Rollman, 1969). In other words, although the summation of energy may be a general sensory phenomenon, nevertheless the unique properties of each sensory system contribute to the processing involved in integration and therefore to the estimate of the time constant of integration obtained for that modality.

The temporal limit of complete summation (critical duration) has been estimated to be approximately 100 ms for vision. For the auditory system, the temporal limit of complete summation found for pure tone stimuli (Watson and Gengel, 1969) has been estimated to be approximately 200 ms.

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Several different theoretical attempts have been made to understand temporal integration as expressed by the reciprocity equation, $I \cdot t = C$. The question whether linear integration functions are empirically descriptive or interpretive (i.e., whether or not they describe the operations of underlying mechanisms) has been argued by theorists. For example, Zwislocki (1969) has argued that the dynamics and time constants of neural adaptation serve to modify the inherent non-linearity of the auditory system's stimulus coding mechanism so that psychoacoustic data may be described by linear integration.

The results reported by Zacks (1970) are relevant to this discussion. Zacks (1970) tested the hypothesis that over some range, visual flashes differing with respect to intensity and duration but equal in energy are equally detectable because they produce essentially identical neural events. He argued that if equal-energy stimuli are equally detectable because they produce essentially identical neural events, then they should be indiscriminable from each other. Zacks provided evidence that even within the range of total reciprocity, equally detectable equal-energy stimuli were discriminable from one another, and was therefore led to reject the hypothesis that equal-energy stimuli produce identical neural events. These results by Zacks for the visual modality lend added weight to the argument that linear integration of energy is empirically descriptive rather than interpretative of underlying mechanisms. However, it is possible that these results reflect the unique properties of the visual system, and that in other sensory systems, fully integrated threshold stimuli do produce identical underlying events and are therefore indiscriminable from one another. If results similar to Zacks' are found for other sensory modalities, the argument that linear integration of energy for a fixed behavioral response is an empirical description rather than indicative of the operation of an underlying mechanism, is strengthened.

The present experiment was designed to test the hypothesis that within the range of total integration, equal-energy auditory stimuli produce essentially identical neural events and, as a consequence, are equally detectable. If equally detectable equal-energy stimuli can be shown to be discriminable, then this hypothesis must be rejected.

Apparatus and Procedure

The research was performed in two stages. In the first stage, psychometric functions were generated for 988 Hz tones. Four subjects took part in this experiment.

Stimuli were trapezoid-shaped tones, of 16 ms and 64 ms duration, whose rise and decay times were 1.0 ms. Stimuli were presented monaurally to the right ear via a pair of Scintrex MKIV earphones. The stimuli were generated by a Heathkit Audio Generator Model IG-72. Tone frequency was calibrated by a Monsanto Type 120 A Counter-Timer. Stimulus energy was calibrated by a Bruel and Kjaer Audio Frequency Spectrometer Type 2113.

Experiment 1

The purpose of the first experiment was twofold: (1) to determine the extent of integration for the range of stimulus duration used in this study, and (2) to obtain detection data for the stimulus pairs to be used in the second experiment to test discrimination.

Each subject was tested over a 12-session period in which the first two sessions served to determine the stimulus energy values to be used in the experiment as well as to provide practice for the subjects.

All testing took place in a Medtechnic Silent Cabin. Subjects were seated facing a panel with a warning light. A three-interval temporal forced-choice technique with feedback for correct responses was used to generate psychometric functions for two stimulus durations, 16 and 64 ms. The duration of each of the three intervals, indicated by the presence of the warning light, and of the two intervals separating them was 1 s. A trial, therefore, lasted 5 s. The intertrial interval was 8 s during which subjects responded. Three to five stimulus intensities were used to generate each psychometric function. Each stimulus intensity was presented 100 times.

The psychometric functions were analyzed by probit analysis on an IBM 370 computer. These results are shown in Table 1 which indicate that all of the functions can be fitted by a cumulative guassian function (χ^2 not significant). In addition, although the absolute thresholds differ for the four subjects, all of the subjects show almost total integration within the duration range studied. That is, an increase in stimulus duration from 16 to 64 ms, a factor of 4, results in a reduction of stimulus energy of 6.5 dB on the average for detection. For three of the subjects , the reduction is close to or exactly 6 dB; for one of the subjects (M.Ch.), the reduction in energy is close to 8 dB.

These results are also illustrated in Figure 1 in which sample psychometric functions are shown for two subjects. Detection levels in standard scores (Z scores) are plotted on the ordinate as a function of total stimulus energy in dB, that is, intensity in dB + 10 times log duration, on the abscissa. Data are plotted separately for the two stimulus

Table 1. Probit analysis of psychometric auditory functions

	Stimulus duration	Intercept (a)	Slope (b)	Mean (μ) threshold dB SPL	Standard deviation (σ) dB	df	χ^2	
Subject								
M.Ch.	16	-0.58	0.17	+3.4	5.9	3	7.64	N.S.
	64	1.8	0.16	-5.0	6.4	2	2.24	N.S.
Difference in means				8.4 dB				
G.L.	16	-0.5	0.132	+3.9	7.6	2	0.19	N.S.
	64	0.2	0.14	-1.3	7.0	1	0.325	N.S.
Difference in means				5.2 dB				
S.Sh.	16	0.3	0.147	-2.0	6.8	2	4.15	N.S.
	64	1.3	0.152	-8.4	6.6	2	0.33	N.S.
Difference in means				6.4 dB				
S.M.	16	-1.1	0.133	8.4	7.5	1	0.054	N.S.
	64	-0.33	0.135	2.4	7.4	1	0.318	N.S.
Difference in means				6.0 dB				
Avérage threshold difference (16-64 msec)				6.5 dB				

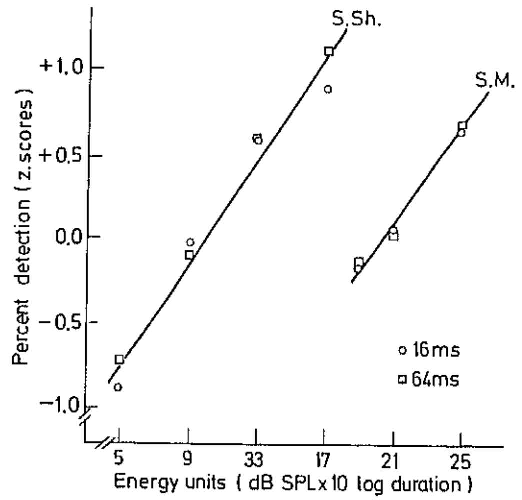

Fig. 1. Sample psychometric functions are plotted separately for two subjects. Detection levels in Z scores are plotted on the ordinate as a function of total stimulus energy in dB, i.e., 10 times log intensity (dB SPL) times duration on the abscissa. See text for full explanation

durations for the two subjects. Note that for these two subjects, a single line can be drawn through the data points representing the two stimulus durations when plotted on a total stimulus energy axis, thus illustrating complete reciprocity or total integration of the 988 Hz tone for the 16 and 64 ms stimuli.

Experiment 2

The second experiment was performed to determine the ability of subjects to discriminate between the two stimuli of equal energy at approximately equal detection levels, but constructed of different intensities and durations. This stage involved choosing pairs of stimuli for each subject such that the two approximately equally detectable members of each pair were equal in energy but differed in intensity and duration (i.e., 16 and 64 ms). The actual stimulus values were determined from the respective psychometric functions. Four such stimulus pairs at four different overall energy and detection levels (20%, 40%, 60% and 80%) were chosen for each subject. For three of the four subjects (G.L., S.Sh., and S.M.), the two members of the equal-energy pair were within 2% of each other at each of the four detection levels since the psychometric functions generated by the subjects were very close to 6dB apart (note Table 1). For example, for subject S.M., the 16 ms member of a stimulus pair nominally detectable at a 40% level was detectable at a 39% level, while the 64 ms equal-energy member of the pair was detectable at a 41% level. For one of the subjects (M.Ch.), however, the two members of the four equal-energy stimulus pairs producing four detection levels differed from each other by 6 to 11%. For subject M.Ch., for example, at a 40% detection level, the 16 ms stimulus produced a 40% detection level while the 64 ms equal-energy stimulus produced a 48% detection level. This occurred because for subject M. Ch., the two psychometric functions were placed further apart than 6 dB (note Table 1).

In this experiment, a three-alternative temporal forced-choice technique was used in which the 16 ms tone was presented as two of the three alternatives while the 64 ms tone was presented as one of the three alternatives (the "different" one). The subject was required to indicate which one of the three tones differed from the other two, i.e., to discriminate between the single 64 ms and the two 16 ms equal-energy tones. Stimuli at each of the four different overall energy detection levels were presented 100 times for each subject. A different energy level was tested at each session. The order of presentation of the different energy levels was random for each of the subjects. Since the actual threshold differed for the four subjects, the overall energy of the stimulus pairs at the four detection levels differed across subjects. The equivalent independent variable for the four subjects was, therefore, detection level.

The results of this experiment were analyzed by a one-way repeated analysis of variance on all 4 subjects. The analysis was repeated deleting the results of subject M.Ch. because of the differences in his actual detection levels as noted above. However, since the results of this analysis did not differ from the first analysis, results of all four subjects will be presented. The results of the analysis of variance are shown in Table 2. These results indicate that discrimination between the 16 and 64 ms equal-energy stimuli changes significantly as a function of detection (or overall energy) level.

The data for each subject were fitted by a linear function by a least squares technique on an IBM 370 computer (Smillie, 1969). The results of this analysis, shown in Table 3, indicate that for all subjects, the linear component is highly significant and accounts for over 99% of the variance ($R^2 \geqslant 0.99$).

Table 2. One-way analysis of variance with repeated measurements. Discrimination as a function of detection level. Data for 4 subjects.

Source	SS	MS	df	*F*
Detection level	11,512.25	3,837.4	3	994.14*
Between subjects	80.75	26.91	3	
Within subjects	11,547.00	962.25	12	
Residual error	34.75	3.86	9	
Total			15	

*$P \leqslant 0.001$

Table 3. Constants of the linear function relating discrimination level to detection level.

	Intercept	Slope (b)	95% Confidence Limits Around Slope (b)	df	*F**	R^2
Subjects						
S.Sh.	-0.96	1.685	±0.137	1,2	724.4	0.997
S.M.	-1.22	1.977	±0.141	1,2	440.0	0.997
G.L.	-0.88	1.731	±0.121	1,2	1,199.0	0.998
M.Ch.	-0.88	1.695	±0.06	1,2	4,293.8	0.999

*$P < 0.005$

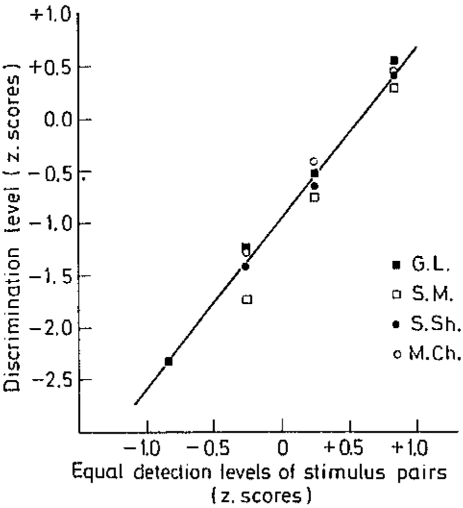

Fig. 2. Discrimination level in Z scores is plotted on the ordinate as a function of detection level in Z scores on the abscissa. Data are shown separately for each subject

The data for the four subjects are shown in Figure 2 in which discrimination level in Z scores is plotted as a function of detection level in Z scores for the 4 pairs of equal-energy, equal detection level stimuli. Note as detection (overall energy) level increases, discrimination level also increases.

A single function can be drawn through all of the data points indicating that for this experiment the intersubject slope variance was low (note Table 3). The data indicate that as the detection level rises for each of the two members of the equal-energy pairs as a result of increases in stimulus intensity, the ability to discriminate the longer duration, 64 ms tone from the equally detectable 16 ms tone also increases. In fact, the increase in discriminability between the two equal-energy, different intensity and different duration stimuli increases at a relatively faster rate than the increase in detectability of these stimuli. This fact is seen by the slopes of this function (Table 3) for each of the four subjects and the fact that the average of the four slopes is 1.772. Increasing intensity thus leads to an increase in detection as well as to an increase in discrimination.

Discussion

The results indicate that discrimination level increases as a function of increases in the energy level of the pairs of equally detectable stimuli. Furthermore, discrimination level increases at a faster rate than detection level as a function of the same parameter, energy. As detection level increases, so does the ability to discriminate between two equal-energy, equally detectable stimuli which differ in the way the energy is packaged. This point is important in rejecting a possible explanation of the data. That is, one may claim that in a three-alternative temporal forced-choice procedure, if the energy of one of the stimuli is at a lower detection level than the other two stimuli, discrimination is possible because two of the stimuli (16 ms, more intense tones) are "heard," i.e., detected, while the other, "different" one (64 ms, less intense tone) is not "heard," i.e., not detected. The fact that the stimulus pairs were not only of equal energy, but also equally detectable when tested alone, and that discrimination proceeded at a faster rate than detection, argues against such an assertion. Discrimination occurs because of discriminable differences arising from the different intensities and durations comprising the equal-energy packages.

There are several possible theoretical frameworks within which these data may be interpreted. On the one hand, these data may be considered as supporting the hypothesis proposed by Zacks (1970) for the visual system that even within the range of complete reciprocity, equal-energy threshold level stimuli do not produce identical neural events and, as a result, are discriminable from one another. The present experiment indicates similar results for the auditory modality. Complete reciprocity of equal-energy stimuli as determined by a detection measure does not guarantee the finding of equality of these stimuli when tested by another behavioral measure such as discrimination. If one accepts this explanation of the auditory data, then they also fit within the hypothesis suggested by Zwislocki (1969) that the psychophysically determined reciprocity equation, $I \cdot t = C$, is only a descriptive device even at threshold and does not necessarily indicate the nature of the underlying neural mechanisms. To emphasize this point of view, these results may be taken to imply that the two stimulus parameters, intensity and duration, may be processed separately within the nervous system, although for the purposes of detection, the auditory system may utilize either parameter in an equivalent manner, thus resulting in what appears behaviorally to be reciprocity.

An alternative framework within which these data may be interpreted relates to the possibility that the same sensory modality may have several time constants. These data may perhaps be understood in the context of experimental results reported for other modalities regarding various and varying estimates of the time constants of energy integration. Evidence has been presented indicating that temporal integration may vary with the response being measured (e.g., Bruder and Kietzman, 1973; Kahneman and Norman, 1964; Raab, 1962). For example, it has been found that the time constants of temporal integration are briefer for reaction time than for threshold (Raab, 1962). In addition, the time constants of temporal integration for vision estimated from data generated by classical techniques are longer than estimates from data generated by signal detection techniques (Bruder and Kietzman, 1973).

Bruder and Kietzman (1973) hypothesized that perhaps the differences in time constants for the reaction time and psychophysical measures they found for threshold level visual stimuli resulted from differences in components of the neural responses underlying the various behavioral measures. They suggest further that the neural mechanism(s) for a behavioral latency response may have shorter time constants and therefore yield a short behavioral critical duration. On the other hand, the neural mechanisms for a psychophysical measure may have longer time constants thus resulting in an estimate of a longer behavioral critical duration. This reasoning implies that various behavioral response measures yield different estimates of critical duration because the time constants of the underlying mechanisms differ. Applying this line of reasoning to the data presented in this paper, we might conclude that the neural mechanisms underlying the discrimination of threshold level auditory stimuli differ from those underlying the detection of the same stimuli and that their respective neural mechanisms have different time constants. In other words, one may retain the hypothesis that behaviorally determined time constants reflect the time constants of underlying neural mechanisms. Emphasis is placed on the different behavioral measures rather than on differences in the neural representation of the stimuli. For detection, stimulus reciprocity was found for the 16 and 64 ms tones indicating that the range of reciprocity extends up to 64ms, at least. For a discrimination response, however, the limits on the temporal range of reciprocity may lie between 16 and 64 ms, thus allowing discrimination between the members of the equal-energy pairs.

It is important to emphasize in this regard that the energy levels used in this experiment were in the vicinity of "threshold," when defined as the 50% detection level. One cannot argue, therefore, that the differences in the integration time constants between detection and discrimination arise because discrimination is a suprathreshold phenomenon while detection is a threshold phenomenon. As can be seen in Table 1, the standard deviations, i.e., the inverse of the slopes of the psychometric functions, for all of the subjects, were between 6.0 and 7.5 dB. Since these functions are guassian in shape, the entire range of intensities used in the discrimination experiment (20% to 80% detection level) did not exceed 8 dB, and the maximum energy level above threshold , i.e., 50% detection level, did not exceed 4 dB. Thus even the discrimination task was within the "threshold" range rather than in the suprathreshold range.

In summary, equal-energy, equally detectable stimuli of different intensities and durations of a 988 Hz tone are discriminable from one another although both are within the limits of complete reciprocity when the response measure is detection. Therefore, one cannot extrapolate from one behavioral measure to another regarding the time constants of reciprocity even at very low intensity levels.

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