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Sensory Performance of Organisms*

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THIS paper is concerned with those aspects of organized neural complexity that permit organisms, such as man, to deal successfully with their sensory environment. Examples presented below illustrate how man, as an organism, detects, orders, and identifies events in his environment to which his sense organs are sensitive. The roles that stimulus intensity and time play in these operations are emphasized, as opposed to those aspects of sensory quality (pitch and hue, for example) for which one might expect the underlying mechanisms to differ rather considerably in going from one sensory modality to another.

Studies of communication processes in the nervous system should be based on a realistic view of the way in which the total organism reacts when it reaches selectively into its surroundings—be it under self-instruction or under instructions from others—to process stimuli that have informational value. This emphasis upon the organism's behavior in communication tasks leads to a preoccupation with certain dependent and independent variables. It leads to an inquiry into the "operating characteristics" of the organism in order to be able to specify, albeit in a statistical manner, its maximum sensitivity, its resolving power, its dynamic range, its characteristics in the frequency and time domains, its information-handling capacity, and so forth.

The data presented in this paper come mainly from *contemporary* psychophysics. Subjects are not asked to introspect, but, rather, to indicate by standardized motor responses (most often verbal responses) whether they judge a stimulus to be present or not, whether they judge two stimuli to differ, whether they can order a set of stimuli or identify members of the set.

Assume that one is dealing with well-instructed cooperative subjects who are skilled in the execution of the expected response and who are familiar with the set of stimuli that will be presented to them.†

Assume also that there is agreement on a program of stimulus presentation and on a method of response analysis. Thus, one must decide whether the admissable response categories shall be simply: "yes" and "no," "same" and "different," "more" or "less," or whether they should include the set of natural numbers. There must also be rules for dealing with false responses (false-alarm rate), and, finally, one must decide whether or not to quantify the temporal aspects of responding in addition to recording the mere emission of responses.

Such considerations may seem unnecessary details that should be left to methodologists, but unless there is a realistic understanding of the measurement and quantification problems in fields like psychophysics and neurophysiology, one can hardly evaluate the store of knowledge they have produced, or understand the relation of such knowledge to the knowledge that exists in the several areas of biophysics.

INFLUENCE OF INSTRUCTIONS UPON THRESHOLD OF DETECTION

The task of detecting the presence of a stimulus includes the classical absolute threshold as well as the generalized "masked" threshold—i.e., detection of the stimulus against a background of sensory stimulation. Such "background noise" refers necessarily to the sense modality under study. Even the best isolation booths do not reduce to zero all unwanted sensory influx other than that under the experimenter's control.

It has long been known that instructions significantly influence both the shape and the anchor points of "frequency-of-seeing" or "frequency-of-hearing" curves. A recent study by Smith and Wilson[2] has forcefully illustrated this dependence upon the judgmental criteria that are suggested to observers. Ten observers were asked to report the presence of a tone in noise. The three curves of Fig. 1 show how the identical group of observers performed this task under three different sets of instructions. Examples of the instructions that were designed to induce a "conservative" or a "liberal" attitude in the reporting of signals follow:

Conservative groups:

"Keep in mind that it is important for you to be sure you hear the tone. In many cases, there will be no tone, and you will be making a mistake if you indicate that you hear one. None of the tones is really easy to hear, but don't push the switch unless you are sure that you heard the tone. If you are in real doubt as to whether or not you heard a tone, assume that there was none."

* This work was supported in part by the U. S. Army (Signal Corps), the U. S. Air Force (Office of Scientific Research, Air Research and Development Command), and the U. S. Navy (Office of Naval Research).

† Experiments parallel to those considered here could be conducted with monkeys or even with rats or pigeons, if appropriate behavioral techniques were used. However, few experimenters[1] have been willing to train their animals thoroughly enough, or to reformulate the required response in a way that was compatible with the animal's behavioral repertory. The short-cut of employing highly motivated and intelligent subjects permits experimenters to bypass a lengthy learning process.

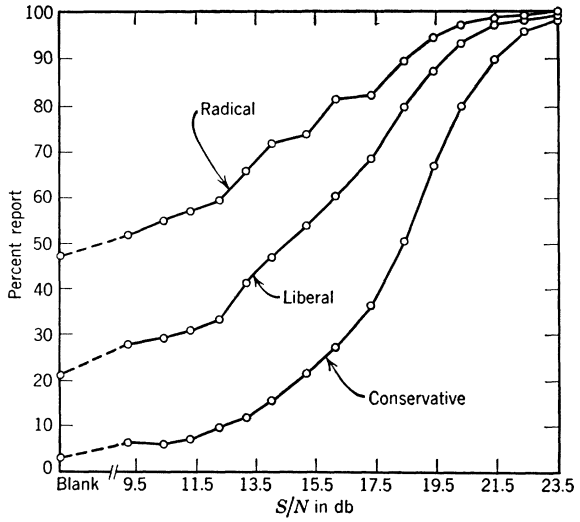

FIG. 1. Cumulative percentage of instances in which the presence of an 800-cps tone was reported as a function of signal/noise ratio. Attitude towards listening tasks is varied by means of instructions (see text). Each of 10 observers made approximately 150 judgments per point.[2]

Liberal groups:

"Keep in mind that all of these tones are hard to hear, and that you will rarely be absolutely sure that you heard something. But if you think you heard something, probably you did—report it. If you are very sure that you didn't hear anything—then don't touch the switch."

The results illustrate clearly that one cannot hope to predict accurately from a knowledge of signal-to-noise ratio alone the performance of a group of observers, even if the task calls for nothing more than the reporting of the presence of a single class of signals against the background of an unvarying noise.

Statistical models of the detection process have been formulated[3] in which performance is predicted not only on the basis of stimulus values and organismic variables; there are additional parameters that are sensitive to instructions and to amounts of reward or punishment. Such models may account for behavior such as is depicted in Fig. 1. A physiological interpretation of this sensitivity of the organism to nonstimulus variables remains to be given, though some physiological phenomena that provide grist for speculation have been reported in recent years.

When tasks that involve some ordering of stimuli are assigned to organisms, three problems are encountered. These stimulus-ordering operations may be listed under the headings of (a) differential sensitivity, (b) identification, and (c) psychophysical scaling.

DIFFERENTIAL SENSITIVITY

Such labels as just-noticeable difference (jnd), differential thresholds, and difference limens have been used to describe the changes in stimulus characteristics that make it possible for an observer to distinguish, with various degrees of certainty, between two stimuli. All of these measures of differential sensitivity are statistical in character and the jnd increases in size if a listener is required to identify correctly the more intense of two sounds in 90% of the trials than if he is required to be correct in 75% of the trials only.

More than a century ago, Weber formulated, on the basis of his own experiments, a generalization according to which the jnd between two stimuli gets larger as the stimuli get larger. This assertion has been called Weber's law, and the expression‡

$$\Delta I/I = k \tag{1}$$

has been written to express this relative constancy of human differential sensitivity. Here, I is the intensity of the reference stimulus, ΔI represents the difference along the intensity dimension that is discriminable (in 75% of the trials, for example), and k is a constant. Weber's law states, therefore, that the jnd will remain proportional to the intensity of the reference stimulus. Today, there exist Weber functions (see Fig. 2) that cover a wide enough dynamic range to provide a fair test of the validity of Weber's law. The data indicate that, at least for auditory and visual stimuli, this relation breaks down as the absolute threshold is approached. Both frequency and intensity discrimination worsen as the stimulus becomes weaker. The existence of the so-called achromatic and atonal intervals[7] is further evidence along these lines. A better fit to the data of Fig. 2 is then provided by an equation of the form.

$$\Delta I = k(I + N_i); \tag{2}$$

N_i has such a value that for low values of I, ΔI depends primarily upon N_i, while for medium and high values of I, N_i becomes negligible.

The introduction of N_i can be interpreted in different ways. Years ago, both Fechner and Helmholtz suggested that Weber's law be modified to acknowledge the presence of intrinsic interfering stimulation that could not be eliminated. In contemporary jargon, one might say that N_i corresponds to the "internal noise level" of the organism. This expression should, however, not be taken too literally. Several theoretical models exist in which a generalized noise term is a crucial feature of the discriminating organism. Thus far, modifications of Weber's law have aimed at agreement with the data near the absolute threshold. There is some evidence that the presence of extremely intense sensory stimulation leads again to some deterioration of discrimination. It is easy to see that the model could be further modified

‡ The symbolic notation employed in writing this Weber fraction or Weber ratio seems to emphasize the intensitive aspects of a stimulus. Actually, what is involved is not necessarily some aspect of energy flux, but rather loose usage of the term "intensity." Thus, fractions have been determined for lifted weights, length of line, pressure on the skin, and so forth, and comparisons between sense modalities have been made on the basis of these numbers.

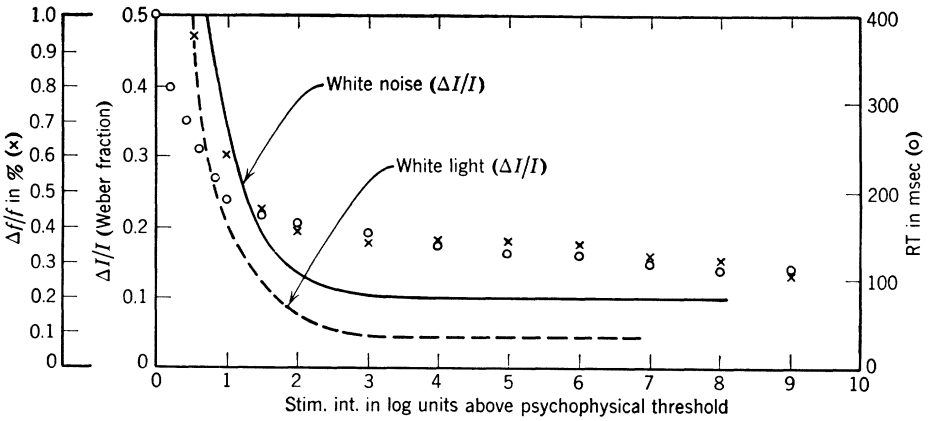

FIG. 2. Just-noticeable differences and reaction times as a function of stimulus intensity. Data on frequency discrimination of a 1000-cps tone after Shower and Biddulph[4]; on intensity discrimination for white light and white noise after Boring, Langfeld, and Weld[5]; data on reaction time after Chocholle.[6]

by the introduction of another term corresponding to an equivalent noise level that would only come into play for large values of I.

One further comment regarding the amount of invariance that it is realistic to expect in psychophysical data. Figure 3 summarizes the findings from more than half a dozen investigators, all of whom were trying to measure man's ability to discriminate pitch. In different experiments, different subjects, several psychophysical methods, several methods of stimulus presentation, and even several response criteria were employed. While it does not seem possible to read from this graph a value for the jnd for frequency, it is possible to point out that practically all of the data lie within the two dashed lines; i.e., their total spread is approximately a decade. The compilers of handbooks or of "Critical Tables on Sensory Performance" would thus be well advised to emphasize those aspects of psychophysical judgments that exhibit what might be called "relative invariance." Instead, they often insist upon quoting numerical values (sometimes with several significant figures), perhaps with the forlorn hope that the users of such tables will take these values with a grain of *ceteris paribus*.

SPAN OF ABSOLUTE JUDGMENT

From data on just-noticeable differences, estimates have been made of the total number of distinguishable sounds, lights, or smells. Usually, the authors of these estimates have simply divided the range over which an organism is sensitive by the corresponding average jnd. Thus, the "auditory area"[9] has been estimated to represent several hundred thousand distinguishable sounds, and the number of distinguishable colors has been estimated to be of the same order.

Several unjustified assumptions underlie these extrapolations. Subjects may find it quite easy to detect a difference between two stimuli without being able to identify either of them. In everyday situations, an individual rarely has difficulties in distinguishing between two other individuals even though he cannot tell which one is Jones and which one is Smith. Absolute identification requires much more information than differential discrimination.

Under the influence of the mathematical theory of communication,[10,11] with its concept of channel capacity, many experiments have been carried out to determine man's capacities to process selective information. By considering man as a communication channel with stimuli for inputs and responses for outputs, it has been possible to estimate maximal rates of transmission through him. The amount of input information can be varied either by varying the amount of information per stimulus or by varying the rate at which stimuli are presented. As Quastler[12] has pointed out, the maximal rate of transmission is limited by two factors: (a) people cannot emit more than 5 to 9 responses per second, and (b) people get confused when they have to discriminate

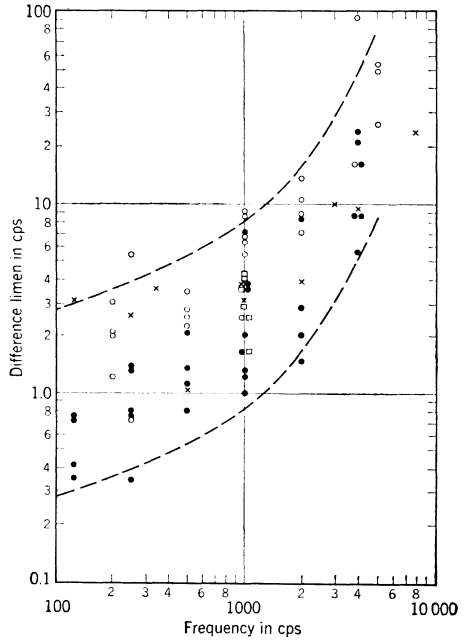

FIG. 3. Data on pitch discrimination reported by several investigators. Different symbols identify different experimental procedures (see Rosenblith and Stevens[8]).

rapidly among too many alternatives. Thus, even under optimal conditions, transmission rates of more than 25 bits per second are hardly ever observed. The type of motor response required and the degree to which stimuli and responses are "compatible"[13] determine the particular figure that will be obtained for the transmission rate.

A different aspect of man's information handling capacity comes into focus if subjects are no longer required to respond as quickly as possible. They now need simply to tell which of several alternative stimuli occurred on a particular stimulus presentation. Given knowledge of the probability of occurrence for the different stimuli and of the accuracy with which the subjects perform, one can calculate the amount of information in these absolute judgments. This experimental paradigm has been much used in connection with "simple" stimuli, such as pure tones or monochromatic lights. The results from these experiments in several sense modalities have led to the emergence of what Miller[14] has called "the magical number 7 plus or minus 2." This number represents the number of alternative stimuli that subjects can accurately identify as long as only one aspect ("dimension") of the stimulus is varied. This magical number thus corresponds more or less to the upper and lower bounds for the "span of absolute judgment." More-precise estimates of performance figures will need to take account—in addition to individual differences—of such experimental conditions as the range of stimulus variation, the spacing of stimuli over a given range, and the number of available response categories. Subjects seem also to perform better if knowledge of results is fed back to them after each response.

Sensory communication in everyday situations is, however, not restricted to making unidimensional judgments. The sounds, shapes, tastes, and smells upon whose successful recognition one's sensory commerce with the environment depends are basically "multidimensional displays." Laboratory experiments with such displays indicate that the span of absolute judgments increases in size as an increasing number of stimulus aspects are varied. Pollack and Ficks[15] obtained 7.2 bits per judgment when they presented to their subjects sounds that varied along six different acoustic "dimensions." This performance corresponds to correct identification of approximately 150 different categories. Comparison of the Pollack-Ficks data (1.2 bits/judgment/dimension) with the characteristic figure for unidimensional judgments (2.3 bits/judgment) shows that, while each new dimension helps to transmit more information, these increments tend to diminish as the dimensionality of the display increases. But it is not known where the asymptote lies for this relation between bits per judgment and stimulus dimensionality. Thus, organisms seem much better in absorbing information from the environment by making several crude distinctions simultaneously, instead of by making extremely precise discriminations of a single aspect of a sensory stimulus. This finding will not surprise those who are familiar with the facts of speech communication where the precise spectral composition of speech sounds is rather unimportant in conveying information. Instead, man's ability to recognize speech sounds seems to depend upon the detection of the presence or absence of "distinctive features"[16] that are thus rather analogous to the dimensions of the acoustic display.

PSYCHOPHYSICAL SCALING

Among all the attempts to establish orderly relations between verbal responses and sensory stimuli, Fechner's law is probably the best known. By the use of indirect methods in which he used the just-noticeable difference as his scale unit, Fechner concluded that psychological magnitude varied as the logarithm of stimulus magnitude. There has been much argument about the measurability of sensation, about the validity of Weber's law, about the legitimacy of the Fechnerian integration of Weber's law which Fechner used to derive his own law; and yet, by and large, Fechner has been correct in predicting that his psychophysical edifice would stand because his detractors would not be able to agree on how to tear it down. In recent years, S. S. Stevens,[17] whose concern with measurement and scaling had led him to investigate systematically many of the fundamental assumptions in psychophysics, has produced a series of painstaking and ingenious studies of how subjects order stimuli by *direct* methods. Stevens did not accept the assumption according to which the unit of resolving power§ is the natural unit for experiments in which observers are asked to order a stimulus continuum by assigning numbers to it and in which these numbers are to reflect the judged or subjective magnitude of the stimuli. Stevens[18] divides perceptual continua into two general classes: continua that have to do with *how much* are called prothetic; continua that deal with *what kind* and *where* (position) are called metathetic. Well-known examples of prothetic continua are loudness and brightness; pitch is an example of a metathetic continuum. On the basis of experiments involving more than a dozen prothetic continua, Stevens concludes: ". . . there is a general psychophysical law relating subjective magnitude to stimulus magnitude . . . this law is simply that equal stimulus ratios produce equal subjective ratios. On numerous perceptual continua, direct assessments of subjective magnitude seem to bear an orderly relation to the magnitude of the stimulus. To a fair first-order approximation the ratio scales constructed by "direct" methods (as opposed

§ This indirect derivation of the scale of psychological magnitude parallels in some sense the extrapolated number of distinguishable sounds or colors. In both instances, the just-noticeable difference is the key concept of quasi-theoretical deductions without regard for operational compatibility.

to the indirect procedures of Fechner) are related to the stimulus by a power function of one degree or another."[18]

Figures 4 and 5[19,20] present two samples of the numerous results obtained. In Fig. 4 there are plotted the magnitude estimates of loudness made by listeners who had not been given standard sounds of fixed intensity for comparison purposes. The eight different intensities were presented irregularly, and the subject estimated the loudness by numbers of his own choosing. These numbers were multiplied by appropriate factors to make each subject's estimate at 80 db the same, namely, 10. The points represent the medians of these "normalized" judgments, and the vertical lines represent the interquartile range of the judgments. By plotting the estimated magnitudes on a logarithmic scale *versus* the logarithm of stimulus intensity, the slope of the straight line is the exponent of Stevens' power function

$$\Psi = kS^n. \qquad (3)$$

Here, Ψ is the psychological magnitude, S is the stimulus magnitude, and k and n are constants. For the stimuli that have been studied, the approximate value of n varies from 0.3 for loudness and brightness‖ to 4 to 5 for electric shocks. The exponent for vibratory stimulation applied to the finger has a value of approximately 1. It is interesting to speculate that these exponents stand in inverse order to the dynamic ranges for the relevant sense modalities. The dynamic range for hearing and vision spans approximately 12 logarithmic units, the range for tactile vibration spans perhaps 3 to 4 logarithmic units, and the range for electric shocks spans only about 1 logarithmic unit. Does the fact that

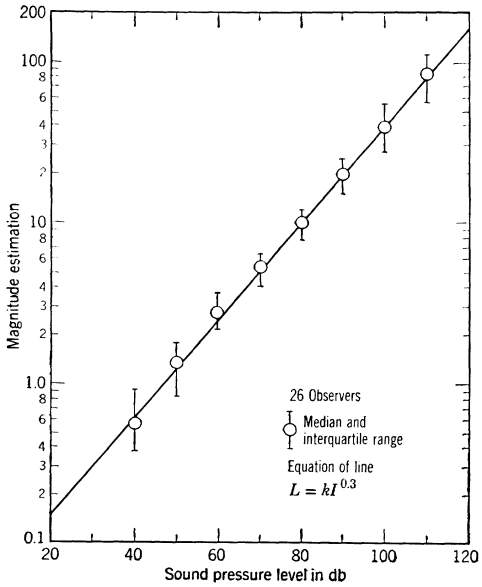

FIG. 4. Magnitude estimates of loudness made with no fixed standard.[19]

‖ The exponent is 0.6 if stimulus magnitude is expressed in terms of sound pressure instead of sound energy.

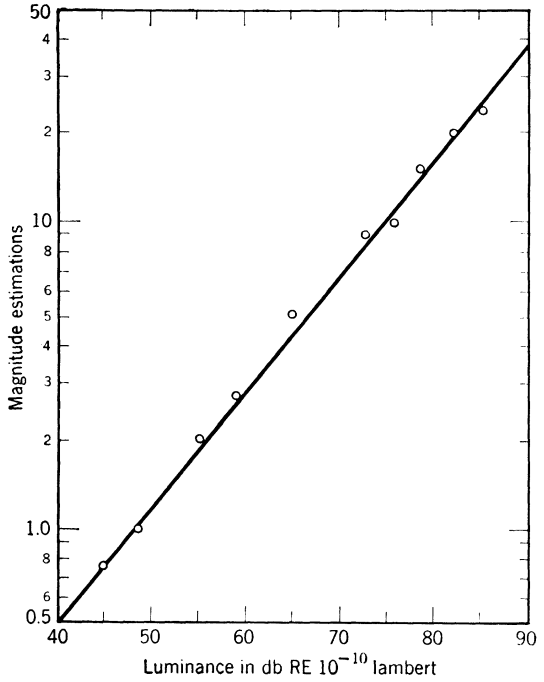

FIG. 5. Magnitude estimates of brightness of a luminous spot; the median estimates of ten observers are plotted.[20]

the product of the exponent multiplied by the dynamic range yields numbers of the same order of magnitude have any deeper significance? Does it reveal anything about the functioning of the sense organ, about the functioning of the nervous system, or does it rather reveal a certain constancy in verbal behavior—i.e., about the way in which people use numbers between the threshold of detection and the threshold of pain?

Another recent study by Stevens[21] deserves to be reported in this context. Once scales of subjective intensity have been established for several sensory continua, can these scales be used to predict what people will do when asked to match directly the loudness of a noise against the subjective intensity of a vibratory stimulus or an electric shock to the finger? Cross-modality matches were made between each modality and each of the other two. To a good approximation, the predicted functions were confirmed by direct experimentation, and the internal consistency of the direct approach to scaling has been further validated by this cross-modality study.

TEMPORAL CHARACTERISTICS OF SENSORY PERFORMANCE

Since Helmholtz's time, experiments on reaction time have been used to make inferences on the processing of sensory signals in the nervous system and on the duration of so-called mental processes such as discrimination, recognition, and choice. It was established that reaction times to sounds, electric shock, and touch were faster than reaction times to visual stimuli; also, that reaction

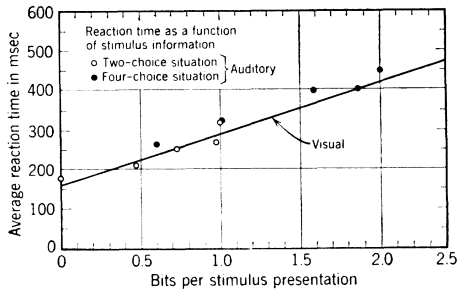

FIG. 6. The straight line represents the best fit to data obtained by Hyman[23] from one of his subjects in response to visual stimuli; the open and closed circles represent reaction-time data obtained by Albert[25] from one of his subjects in response to auditory stimuli; here, the stimulus set was composed of either two or four elements.

times decrease—at first rapidly and then more slowly—as the intensity of a sensory stimulus is raised above threshold (Fig. 2).

In addition to these data on simple reaction times, other experiments have attempted to assess the effect of task complexity on the speed of more discriminative reactions. It has been shown that reaction time increases as the stimulus ensemble increases in size and as its members become harder to distinguish from each other. This whole topic had lain more or less dormant for several decades until it became obvious that the application of certain concepts from information theory might make it possible to explore another aspect of man's capacity to handle information. A series of experiments[22–24] indicated that, at least over a certain range, choice time (or disjunctive reaction time) was proportional to the average amount of information transmitted per stimulus-response event. This finding applies equally well to visual as to auditory stimuli (see Fig. 6), and there is sufficient agreement between the data obtained by different experimenters that it is possible to talk about a characteristic figure for the "rate of gain of information" whose value lies near 6 bits per second. It is not possible to account for these time intervals in terms of delays on either the afferent or the motor sides of the nervous system. Enough is known about the latencies of evoked electric activity to permit one to say that these events consume only a fraction of the time involved in even the fastest reaction. The discrepancy becomes much greater, of course, upon considering sensory stimuli that are barely above the absolute or masked threshold or reaction times that involve complex discrimination. Thus, one must infer that a large fraction of the total reaction must be spent in "central information processing."

Recent experiments by Davis[26,27] and others throw some new light on these inferences. Davis presented to his observers two visual stimuli in succession and asked them to respond to each stimulus in turn. He then varied the interval between his two stimuli randomly between 50 and 500 msec. As long as the separation was more than 250 msec, the reaction time to either stimulus was approximately 200 msec; but when the time interval between the two stimuli fell below 250 msec, the second reaction time increased sharply. The second reaction time reaches its maximum value, approximately 400 msec, for an interval of 50 msec. The same phenomenon occurs when one stimulus is visual and the other is auditory, no matter what their order. Next, the subjects were instructed not to respond to the first of two lights. The results show little improvement over the delays that occurred when motor responses were made to both signals; the only difference was a slight shortening of the second reaction time, by about 20 to 30 msec. In a final experiment, the subjects were asked to make a "response" without a signal having occurred. Following the pressing of the key, a light came on (after an interval that was again randomly varied between 50 and 500 msec) to which the subjects were required to respond. This time there was no additional delay for any time interval. The subject was just as efficient in responding to a signal that came 50 msec after he pressed the first key as he was in dealing with a signal that came 500 msec afterwards. It would thus appear that the actual performance of the response does not contribute much to the delays that are observed, but that these delays are imputable to the processing of a signal that is still going on when the second signal is presented. There is further evidence that emphasizes the amount of time that central processes play in the handling of sensory information. In hearing and in vision, there is almost perfect integration of energy at the absolute threshold, as long as the stimulus is being presented for time intervals that are shorter than 200 msec. There is a whole class of phenomena in both hearing and vision in which a strong succeeding stimulus interferes with the "proper" analysis by the nervous system of a preceding weaker stimulus. The shorter the time interval between the two stimuli and the greater the discrepancy in intensity, the more severe is the interference. Since the delay times on the afferent side of the nervous system are longer for weak stimuli than for strong ones, the more intense stimulus has a chance to "catch up." However, the time intervals involved are sufficiently long that these differences in delay times along the ascending pathway are hardly the whole story. There is the further fact that interference with the more complex discrimination seems to be effective over longer time intervals than with more primitive tasks (such as simple detection of a preceding stimulus).

The preceding illustrations all point to the conclusion that the analysis of sensory information is a time-consuming task that occupies an organism's central nervous system in relation to the amount of information to be processed. This is hardly surprising; yet, it is often overlooked in practical situations.

The foregoing briefly reviews man's sensory performance as it appears when examined by the quantitative methods of contemporary psychophysics. Organisms

are able to deal with the sensory bombardment that impinges upon them by being satisfied to make crude discriminations, unless specifically instructed to make precise ones (at the cost of spending more time making them and of neglecting other sensory events than those under analysis). The flexibility of organisms in switching from one sense modality to another, from one aspect of sensory display to another, is bought at the expense of relatively low rates for the transmission of information. The mere existence of organisms seems to entail a high, internal noise level that prevents responses to environmental stimuli from being anything but statistical in character. As long as thresholds of tolerance are not approached, the more energy a sensory stimulus delivers to an organism, the higher is the probability that the signal will be processed in the central nervous system with both discrimination and dispatch. One may paraphrase this situation by saying that the higher the energy level of a sensory signal, the greater the redundancy with which the representation of this signal will be handled in the central nervous system. These are some of the considerations that led us to select certain aspects of the electrical activity of the nervous system for quantitative study.

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