

cannot observe the graded response of a receptor. In natural conditions, he has no information about latency and accordingly is unlikely to have evolved methods of analysis dependent on it. (In an experiment, he may have such information, and this may affect his response, especially in detection tasks.) He probably has no mechanism that can "count" spikes with any accuracy over a long period.

The information reaching the brain is in the form of a series of discrete, identical events – a point process. The subject's task is to decide when this irregular sequence conveys a message of sufficient importance for him to take some action. His problem is a statistical one, more specifically, one in the field of decision theory and the analysis of point processes. It may be interesting to examine a model, of the simplest possible type that is at all biologically plausible, of a mechanism that could carry out this task.

Suppose each impulse causes a unit change in potential in some analyser, and that the potential difference decreases at a rate proportional to its magnitude, so that in an interval t with no impulse it will fall by a factor e^{-kt} . Suppose that impulses arrive randomly at a rate λ per unit time, and that the subject responds when the potential difference reaches some criterion value. Then, starting from zero potential difference at $t = 0$, it is easily shown that the mean at time t is given by

$$M = \frac{\lambda}{k} (1 - e^{-kt}) \tag{1}$$

This gives an approximate relationship between the criterion M and the response time (of the analyser) t . Strictly, the response time is related to the first passage time to M , rather than to the mean, but often the difference will be unimportant.

Now suppose the relationship between λ and the light intensity I is $I = e^{\lambda} - 1$. This implies that λ is proportional to intensity at low levels and to log intensity at high levels. Then

$$I = \exp\left(\frac{Mk}{1 - e^{-kt}}\right) - 1 \tag{2}$$

This is the relationship between intensity and response time for a criterion M . The slope of the plot of $\log I$ against $\log t$ is

$$\frac{d(\log I)}{d(\log t)} = \frac{IMk^2 e^{-kt}}{\left\{1 - \exp\left(\frac{-Mk}{1 - e^{-kt}}\right)\right\} (1 - e^{-kt})^2} \tag{3}$$

For large t , the limiting value of I is $e^{Mk} - 1$. For small t , the effect of decay becomes negligible, and the slope tends to $-M/t$, giving supersummation for large M and small t . Unit slope corresponds roughly to $t = M$, and this gives

$$\text{Critical duration} = M \left\{ \exp\left(\frac{Mk}{1 - e^{-Mk}}\right) - 1 \right\} / (e^{Mk} - 1) \tag{4}$$

which increases with M .

The model is, of course, an oversimplification. It ignores effects that are known to occur in nerve cells. In particular, trains of nerve impulses are more regular than the Poisson process postulated here, and adaptation has been neglected. These effects would tend to give the smooth curve of equation (3) a more angular appearance. Also, for very short durations and intense flashes, the receptor response itself follows Bloch's law; the duration and intensity depend only on the product of illumination and exposure time, and t in equation (1) no longer has any relation to exposure time. At this stage, the $\log I / \log t$ plot would again have unit slope.

Thus, the model predicts most of the features of "process" responses described by W & K. Bloch's law applies for very short high-intensity flashes; this section of the curve may not appear if the criterion is not reached for such flashes. Rather longer flashes gives supersummation provided the analyser response reaches this stage before the impulse train obeys Bloch's law. Next, total summation is followed by partial summation, the curve eventually levelling to the minimum intensity capable of eliciting the criterion response.

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The role of storage and processing time in temporal-summation phenomena. W & K offer a stimulating synthesis of some possible relationships between observations in single nerve cells of *Limulus* and behavioral studies of humans.

Their paper has the potential for establishing a precedent for integrating empirical research and theory across these widely disparate enterprises. The central phenomenon in their theorizing is temporal summation, the observed tradeoff between intensity and duration of a stimulus in order to produce a constant response. Traditionally, the critical duration for a given sensory system has been viewed as a relatively fixed period; W & K propose that physiological measures vary with the response features and that behavioral measures change with the task of the observer.

Although W & K are directly concerned with the dynamics of visual information processing, they do not address the concepts of a storage structure and information-processing time. The critical-duration concept requires some kind of accumulator storage that allows energy to be summed across time. The effects of stimulation would not be cumulative if no storage existed. In addition, the length of time that the sensory consequences of a stimulus are stored and available for processing critically influences the degree of resolution of the stimulus. One model of these concepts evaluates performance in terms of d' values, which reflect the degree to which the test signal has been resolved to perform the task at hand (Massaro, 1975 *op. cit.*). The measure provides a valid index of stimulus resolution, since it has been shown to be nearly independent of decision biases that might distort other dependent measures. Resolution of the test signal is a temporally extended process, not an instantaneous occurrence. As measured by d' , resolution is a negatively accelerating growth function of processing time t

$$d' = \alpha(1 - e^{-\theta t}) \tag{1}$$

in which α represents the signal-to-noise ratio of the test stimulus and θ the rate of processing this information during the available processing time t .

The processing time t is equal to the duration that the test signal remains in a preperceptual storage. The signal remains in preperceptual storage during the actual stimulus presentation and for a short time after it is terminated. Stimulus resolution of a long-duration stimulus will approach α , since processing time is essentially unlimited. If the duration of the test signal in preperceptual storage is relatively short, however, resolution will not approach α . The preperceptual storage of the test signal can also be terminated prematurely by the presentation of a second stimulus, that is, a backward masking situation. Given a short-duration stimulus, resolution will remain lower than α as an inverse function of the time between that stimulus and a second stimulus.

Performance for short signals is described by

$$d' = \alpha(1 - e^{-\theta t_s}) \tag{2}$$

for $t_s < t_D$ and

$$d' = \alpha(1 - e^{-\theta t_D}) \tag{3}$$

for $t_s > t_D$ where t_s is the time between the onset of the test and following masking stimulus and t_D is the duration of preperceptual storage. In this model, processing occurs during and after the critical period, and only the value of α varies with changes in stimulus intensity and duration. The important question is whether the model can generate supersummation in addition to traditional critical-duration results. Unfortunately, the model predicts discriminability values derived from response probabilities, whereas most studies have used intensity and duration values required for a specific response criterion, such as 75%. Although the data fall outside the quantitative domain of the model, a qualitative analysis is still possible.

There are three possible outcomes of an experiment varying intensity and duration of the test signal: summation, summation failure, and supersummation. According to the model, summation occurs within the period in which the direct tradeoff between intensity and duration does *not* change α , θ , or the processing time t_D . In this case, the effective signal-to-noise ratio and the rate and time for processing do not change when intensity and duration are traded off during the period of the critical duration. Summation failure occurs when the effective signal-to-noise ratio cannot be maintained by trading duration for intensity. Outside of the critical duration, equal energy signals give smaller values of α as duration is increased. Summation failure reveals that the potential increase in processing time with increases in test-signal duration did not compensate for the lower signal-to-noise ratio.

The most interesting result for the model is supersummation. Supersummation occurs when short signals suffer from insufficient processing time because of limited time t_D in preperceptual visual storage. If duration and intensity are directly traded to hold energy constant, then the shorter signal must produce an α that is as large as or larger than the longer signal. The α 's would be equivalent if two durations were both within the critical duration, whereas the α value would

decrease as the duration of a signal was increased beyond the critical duration. Supersummation cannot result from changes in α and, therefore, must result from differences in the processing time available. Supersummation occurs because a longer stimulus remains longer in preperceptual storage, and this increased processing time allows better resolution.

W & K observed supersummation in *Limulus* reflex tail movement evoked by light. The authors use the long period of supersummation (4½ sec) as the period of integration of the receptor signal. However, it could be the case that sensory responses to short signals with high intensities decay rapidly in storage and are not available for sufficient processing time to generate the appropriate response. Lengthening the stimulus duration increases the time that the sensory signal remains available in storage, allowing for longer processing time and, therefore, a higher likelihood of a response. It follows that the intensity of the signal can be decreased disproportionately for longer durations since more processing time is available. The numerosity judgments by Hunter and Sigler (1940 *op. cit.*) can also be interpreted in this manner. Small display sizes can be counted in parallel at a glance, and intensity and duration of the display trade off as they should. Larger displays require serial counting, and duration of the display is much more critical for accurate performance than is intensity. It follows that supersummation is more pronounced as display size is increased.

At this stage, the description of the results in terms of the model may seem relatively arbitrary. However, the interpretation follows directly from using the model in studies of human information processing (Massaro, 1975 *op. cit.*). In order to test the model within the critical-duration literature, it is necessary to vary processing time in addition to varying intensity and duration of the test signal. The most direct manipulation of processing time would be within the context of a backward-recognition masking paradigm (Massaro, 1975 *op. cit.*).

Finally, an alternative explanation is possible for a study discussed by W & K. They interpret some findings by Leibowitz, Myers, and Grant (1955 *op. cit.*) as evidence for semantic recoding of visual localization but not for visual detection. Although detection responses followed temporal-summation rules, localization responses did not. The localization error of detected flashes did not depend on how often a flash was actually detected. One limitation in this analysis is that localization errors were made conditional on correct detections, whereas correct detections were *not* conditional on correct localizations. It is just as likely that detection responses would also fail to give temporal summation if they were made conditional on correct localization. These data are not necessarily inconsistent with the possibility that detection and localization give similar temporal-summation results.

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A neuromuscular circuit model of mental activities. I applaud the innovative work and general approach of W & K and emphasize with them the importance of the historic and contemporary problem of measuring temporal properties of mental activities. At the same time I suggest consideration of a more general model than the one that is implicit throughout their article. The neuromuscular circuit model is more general, in that it allows for the possibility that mental activities are not exclusively a brain function but may be contributed to by several systems throughout the body.

To be brief and excessively simplistic, one may assume that mental activities are exclusively a brain function, or that they are also generated by more extensive internal information-processing circuits involving interactions between the brain, receptors, and effectors. A central-peripheral circuit model of mental activities has a long, revered history and is consonant with an impressive number of empirical findings, as has recently been summarized (McGuigan 1978). Norbert Wiener described this type of model in his classical *Cybernetics*:

"The central nervous system no longer appears as a self-contained organ, receiving inputs from the senses and discharging into the muscles. On the contrary, some of its most characteristic activities are explicable only as circular processes, emerging from the nervous system into the muscles, and re-entering the nervous system through the sense organs, whether they be proprioceptors or organs of the special senses" (1948, p. 15).

A century earlier Alexander Bain espoused a similar model:

"The organ of mind is not the brain by itself; it is the brain, nerves, muscles, and organs of sense. . . . We must . . . discard forever the notion of the

sensorium commune, the cerebrum closed, as a central seat of mind, or receptacle of sensation and imagery" (1855, pp. 18-19).

In short, mental activities are generated as codes carrying information that is processed within neuromuscular circuits. Mental activities are thus not in a separate domain from physical activities, but they *are* physical activities. The model allows for the generation and transmission of a greater variety of internal codes, providing increased opportunity to account for the numerous complexities of mental life. Thus, different, parallel, multichannel coding processes explain linguistic, emotional, and other nonlinguistic components of mental activity, as illustrated in Figure 1.

Linguistic components of mental activity thus may be accounted for in terms of interactions between the brain and speech musculature through a phonetic code, and between the brain and somatic skeletal musculature by means of an allographic code. "Thing" (including visual) components of mental activities may be accounted for with referent codes interacting between the skeletal musculature and the brain. And emotional components of mental life may involve affective codes between autonomic, somatic, and central nervous systems. The adoption of a model that incorporates intracerebral loops, but also allows for the possibility of interactions among the brain and various other bodily systems, increases our chances of arriving at "the truth"; in comparison, a model that assumes *a priori* that mental activities are exclusively a function of one bodily system (e.g. the brain) would blind us to possible contributions of noncentral systems. If research indicates that noncerebral systems are not involved in neural activities, they may be dismissed from further consideration.

The optimal method for testing a central-peripheral circuit model of mental activity ("sensation, perception, cognition, and memory," plus dreams, hallucinations, imagination, and the like) is that of the psychophysicist. By placing sensors at selected bodily regions during the performance of mental activities, the psychophysicist can, with extremely sensitive electronic equipment, study minute electrical components of the internal, information-processing circuits that generate "mental activities"; these electrically-sensed events are often less than one microvolt in amplitude. By temporally relating electrical signals as they occur in selected bodily regions, one can infer sequences of various central and peripheral events during mental activities. The psychophysicist's direct approach to the timing of mental activities can thus supplement the indirect, yet viable, approach of W & K. One illustration of this strategy appears in Figure 2. While details of this study need not concern us, the general paradigm is that the events plotted in Figure 2 occurred at about the time a subject silently answered a question as either yes or no. The interpretation was that events occurring at about the same time in the temporal cortex, passive arm, lips, neck, and eye were possible components of a complex reaction pattern while the subject was silently answering the questions. These complex feedback loops might function to integrate the activity of the speech musculature (lips, tongue, etc.) with that of the speech regions of the brain, and with that of the eye, related perhaps to a covert nod or shake of the head (indicated by the response in the neck region). Concomitant with this intraperipheral, interperipheral, and central integration, in which the subject reached a yes-no decision, and part of the almost simultaneous running off of these feedback loops, a "command" was issued to the passive arm that was inhibitory; that is, before the active arm could overtly respond to indicate to the experimenter whether the subject answered the question yes or no, the passive arm was commanded not to respond, as indicated by the earlier

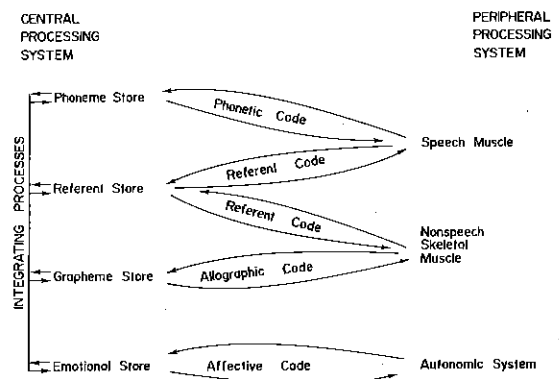


Figure 1 (McGuigan). Peripheral-central information processing with resultant meaning and emotional reactions.