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# ATTENTION IN TIME DISCRIMINATION AND REACTION TIME

*by Alfred B. Kristofferson*

Prepared under Contract No. NAS 2-1790 *by*
BOLT BERANEK AND NEWMAN, INC.
Cambridge, Mass.
*for*

**NATIONAL AERONAUTICS AND SPACE ADMINISTRATION • WASHINGTON, D. C. • APRIL 1965**

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# ABSTRACT

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This paper summarizes a year of research on attention conducted by Bolt Beranek and Newman, Inc under Contract NAS2-1790 with the National Aeronautics and Space Administration through its Ames Research Center.

A theory of attention is developed which emphasizes its temporal features. Attention is considered to be a central-neural control of information flow which is accomplished within the central nervous system. The hypothesis that it is all-or-none in nature is developed at length. The theory is framed in a sensory context and the experiments are done in that context. Alternative assumptions, which lead to different quantitative models of the theory, are presented.

Two very different methods for measuring the parameters of the theory are developed in detail. One of these involves the ability of the human to discriminate two independent sensory events as successive rather than simultaneous, and the other concerns the influence of channel uncertainty upon reaction time.

Six experiments are reported which were undertaken in an effort to measure the theoretical parameters in the two different ways and to do this with sufficient precision to test the theory on each of a number of individuals separately. The following are the major conclusions:

1. The same sensory signal may or may not be processed by attention. Whether it is so processed depends upon the use made of its information content. Channel uncertainty does not effect reaction times which depend upon the mere detection of a signal, but it does effect those which are contingent upon discriminating one signal from another.

2. Practice is an important variable. Attention is not relevant to detection reaction time after extensive practice, but practice does not have the same effect upon discrimination reaction time.

3. The Four-signal discrimination reaction time procedure in Experiment 4 cannot be used to estimate parameters for single individuals because of excessive intra-individual variability. The group data, however, are meaningful.

4. The average minimum time which must separate two independent signals for them to be discriminated as successive 100 percent of the time is 62 msecs. (Experiment 5). The average time required to switch from one sensory channel to another is also 62 msecs. for the same fourteen subjects as measured by the Four-signal Discrimination Reaction Time procedure.

5. A Three-signal Discrimination Reaction Time procedure (Experiment 6) seems to be adequate for use with individuals, although data are available for only two subjects.

6. The hypothesis that the switching of attention is controlled by a periodic mechanism and that switching can occur only once every M msec. receives support in several ways from Experiments 4, 5, and 6.

7. Evidence is accumulating which suggests that different individuals may behave in accord with theoretical models which differ in detail. Whether this is true will be decided by future research as will the validity of the assertion that the general theory here proposed can generate models which are sufficient to explain the behavior of all individuals in terms of a single set of theoretical parameters.

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# A THEORY OF ATTENTION

This paper proposes a theory of the "microstructure" of attention. It is a theory which describes single attentive acts, stressing their temporal characteristics. It yields models which allow quantitative comparisons to be made.

Attention is thought of as a selective control of information flow in the central nervous system. This selective control or gating of information is accomplished within the central nervous system by a central-neural mechanism. This mechanism has the logical properties of a many-poled highly-flexible switch which funnels messages into a single processing channel. The selection of messages which is accomplished via overt behavior, such as eye movements, is not considered here.

The messages we will be concerned with are sensory messages arriving over the exteroceptive systems. It may well be the case that the same attention mechanism controls other kinds of messages, such as those stored in memory, but because it is essential that we be able to control the temporal features of the messages with great precision in the experimental work, and must, therefore. use messages which are closely correlated in time with events which can be manipulated, this theory will be framed in the sensory context.

Four general assumptions form the base of this theory. They are: (1) there are independent input channels; (2) an input message can signal the attention mechanism to scan its channel; (3) the channel being attended at a specified moment can be predetermined, at least under ideal conditions; and (4) when a signal to switch to a new channel is received, some time elapses before the switching is complete. A discussion of these assumptions follows in which the first two will be stated with sufficient specificity to enable them to be used unchanged in later derivations. The third and fourth are left in a somewhat more general form so that different versions of them can be stated in later sections in order to specify different experimental operations as relevant to the theory, and also to generate different quantitative models of the theory.

## General Assumptions

Assumption 1. There are independent sensory channels.

Messages are transmitted over projection pathways from receptors to sensory "display areas" in the brain. The projection pathways are divided into functional channels, each with its own display area, which are independent of each other in two ways. They are independent in that it is possible to insert at least some inputs into one channel without effecting the events which occur in the display areas of other channels. Also, they are independent in the sense that they are independently operated upon by the attention mechanism so that, at any moment in time, attention can be "directed at" or "aligned with" only one channel display area.

The attention mechanism is conceived of here as a very simple, all-or-none switch; as a mechanism which determines which single channel will be allowed to transmit information further along through part of the system at each moment.

One might object to an all-or-none conception, preferring to assume that attention is a matter of degree. After all, introspectively the process seems to have certain quantitative features. This objection may have force. An all-or-none assumption may provide an incomplete description; however, all that is necessary is that it be at least a part of the picture, and that channels which are independent in the all-or-none sense do exist. On the other hand, an all-or-none theory may be enough to explicate the entire phenomenon. Discrete theories of apparently continuous phenomena are often quite sufficient.

If there are such independent channels within the afferent nervous system, it should be possible to define their boundaries. Unfortunately, we cannot do so with any precision at the present time, and it must be recognized that this is an important problem yet to be solved. <u>We will assume specifically for present purposes that channels situated in different sensory modalities are independent</u>. And we will develop the theory, and perform the first experiments, for the case of two such channels, one auditory and one visual. If there are independent channels, it is most likely that two selected from separate modalities are examples.

Once a valid model of the attention mechanism has been constructed for the simple inter-modality case, it will be possible to use it as a criterion against which to judge whether the members of any set of signals occupy independent channels. It will be possible to locate boundaries within, _e.g._, the spatial visual field, or along dimensions such as hue or brightness and also to determine whether the boundaries are fixed or whether they depend upon the identity of other channels which are simultaneously relevant or, perhaps, upon the density or kind of information displayed within each channel.

To summarize, it is assumed that a specific spot of light and a specific tone produce afferent excitations which cannot be gated simultaneously by the attention mechanism. It must be pointed out that this does not necessarily mean that the two excitation patterns may not overlap to some extent. It means only that those excitation elements produced by the light which are _relevant to the behavior being measured_ are independent of the relevant excitation elements produced by the tone.

_Assumption 2_. _A signal in an unattended channel can "attract" attention_.

Under ordinary conditions at least, attention does not switch among channels in any rigid, fixed order, nor is the order fortuitous. Many factors conspire to determine which of the many sensory channels will be scanned at any instant. Among these factors are the immediate past history of stimulation and response, the expectations of the subject, his motivational state, and, perhaps, inherent characteristics of the channels.

Excitation arriving in display areas may have an influence on the direction of attention too and, while such an assertion may seem paradoxical, it is necessary to make it.

It is assumed that, if the attention mechanism is gating information from channel A at the moment a message arrives in the display area of Channel B, the new message may signal the attention mechanism to switch its gating function from A to B.

It would be more realistic, perhaps, to state that in general the message in Channel B increases the probability that B will be scanned next. However, for present purposes it is necessary to assume that under certain conditions this probability can be unity. This sets the requirement that experiments which test this theory must make every attempt to maximize this probability. To accomplish this, the experimentally relevant channels must be defined unequivocally for the subject, the signals must be clearly supraliminal, and the subject should be highly practiced in a specific task and be able to rely upon his expectations about when and where signals will occur.

This assumption implies that at least some sensory information can be processed and can have psychologically important effects without passing through the system controlled by the attention mechanism. In the case of this assumption, certain messages are able to determine which channel will be scanned by the attention mechanism without having to be scanned themselves. And to accomplish this, these messages must convey information which identifies specific channels.

Therefore let it be stated explicitly that some classes of information may be utilized by the organism even though they are transmitted over channels which are not controlled by the attention mechanism. It is one more long-range problem to discover empirically which kinds of tasks require attention-controlled information and which do not.

Assumption 3. The channel which will be attended at some specified future point in time can be controlled experimentally.

If it were possible to monitor the attention mechanism so as to know which channel is being scanned at every moment, the problems associated with research on attention would be vastly simplified. Obviously, that cannot now be done directly and some compromise must be found.

Depending upon the experiment to be analyzed, different versions of this assumption are sufficient for the analysis, and it is possible to contrive experimental conditions so that it is not unreasonable to believe that the subject can comply with the assumption.

For example, sometimes the assumption that the probability is unity that channel A will be scanned at time T is sufficient for a specific experimental condition. Several features of the experimental situation can be manipulated in the attempt to make $P_A$ approach one. In the first place, channel A should be clearly defined for the subject. This is done by presenting signal A for some entire interval of time before and up to the critical time T. For this reason, experiments might use stimulus offsets as the critical signals. Furthermore, the subject should be given extensive practice so that he knows precisely how long after the onset of the stimulus the critical instant will occur. Also, he should know that if any signal offset occurs, it will be in channel A.

The only uncertainty on the part of the subject under conditions for which $P_A = 1.0$ must be assumed may be whether signal A occurs at the critical instant or whether no signal at all occurs.

In general, if a subject is to behave in a way which approaches the theoretical ideal, it is probably necessary to provide him with completely sufficient information, to design the task so that his performance is maximized if he behaves in the ideal manner, to give him feedback contingent upon his performance, and to allow him ample time to learn the task thoroughly.

<u>Assumption 4</u>. <u>If attention is directed at channel A at the moment the mechanism is signalled to switch to channel B, some interval of time, $\delta$, must elapse before the switching to channel B is accomplished</u>.

This "switching time" of attention, the time between the receipt of a signal to switch and the completion of the switching operation, is a major theoretical variable and the first experiments will be designed in an attempt to isolate it, to describe its probability distribution, and to define a mechanism which will generate the distribution.

The probability distribution of switching times, which will be called "$\delta$-distribution," has a mean of $\Delta$ and a variance of $\sigma_\delta^2$.

## Models of the Attention Mechanism

The four general assumptions which have been discussed above overlap very little. The first two primarily lay down the essential structure of the theory. The third and fourth mainly describe aspects of the functioning of that structure. Each of the first three has essential implications for operationalizing the theory; each of them dictates certain features which must be incorporated into any experiment designed to test the theory; they provide the definitions which coordinate the theory to data. The first three assumptions also suggest many relevant experimental manipulations.

The fourth assumption, concerning the existence of distributions of attention switching times, is different. It seems, at the present time at least, to prescribe nothing about experimental control. It does not provide avenues into the mechanism. It is the most hypothetical of constructs.

Therefore, we will proceed by fixing "values" for the first three assumptions and "allowing" the fourth to vary by postulating different forms for it.

Figure 1 diagrams the specific class of models which will be developed further for experimental testing. Two sensory channels are involved, one visual and one auditory. A light signal activates the visual channel and, after a delay $d_v$, a message arrives in the visual display area. The message in the visual display area may bypass the attention mechanism entirely or it may be necessary for it to pass over the pathways controlled by the mechanism. In the latter case, the message can be relayed further through the system more rapidly if the attention mechanism is gating information from the visual display area at the moment the message arrives than if attention is directed at some other channel at that moment. The direction of attention is indicated by the solid arrow in Figure 1. If some other channel is being scanned at the moment the message arrives in the visual display area, the message may deliver a signal to the attention mechanism, informing it to switch over to the visual channel.

Behavior which is dependent upon attention is denoted by $R_A$ in the diagram. If one is observing behavior of this class, and if the behavior is sensitive to the temporal relationship between signals in various channels or to the temporal relation between signal and behavior, the additional delay introduced by the attention switching mechanism may be measurable if one can sort experimental trials into two classes: those on which attention is directed at the relevant

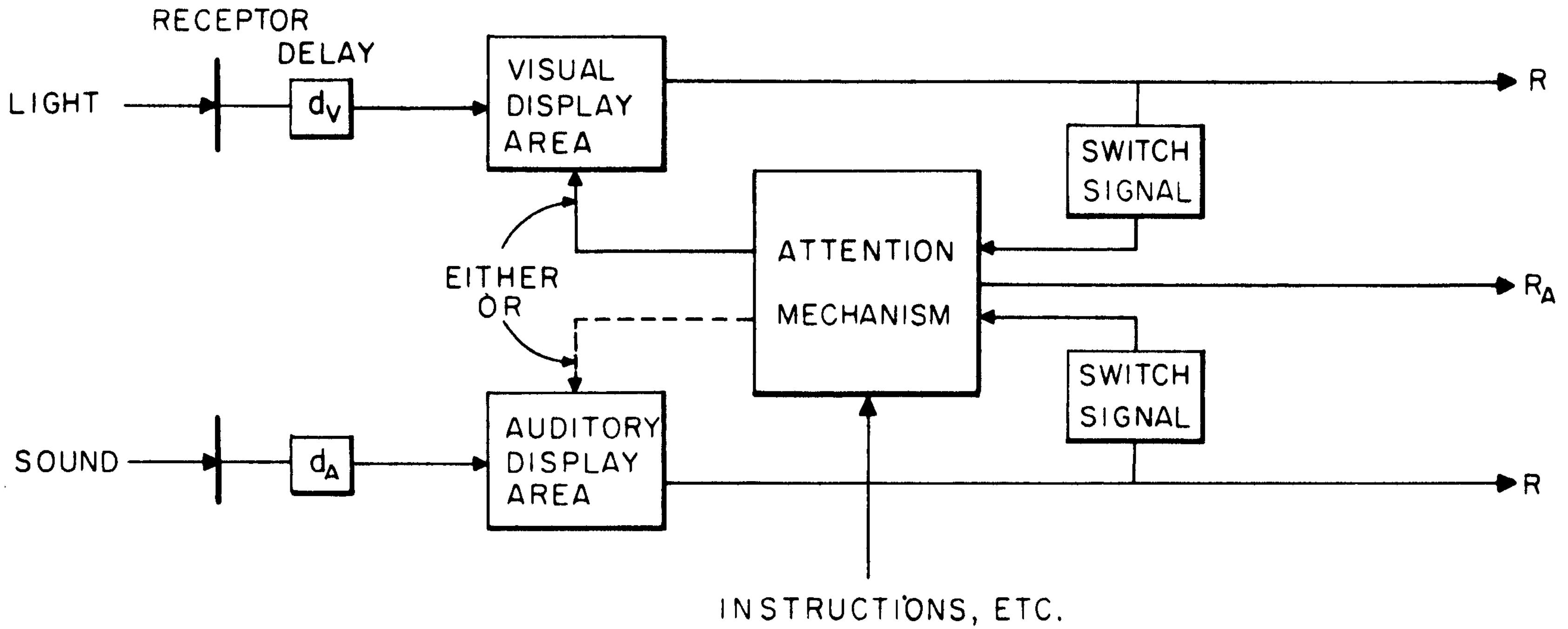

FIG. 1 THE POSITION OF THE ATTENTION MECHANISM IN THE NEURAL INFORMATION PROCESSING PATHWAYS.

channel at the moment the message arrives and those on which it is not. The switching time of attention is then an inference based upon the relationship between two temporal relationships.

The delays which exist in the afferent channels are highly important and the fact that they cannot be assumed to be equal slightly complicates the interpretation of data. It is necessary to include $d_v$ and $d_a$ explicitly into any model. Many lines of evidence, such as the results of simple reaction time experiments, suggest that under most conditions $d_v$ is greater than $d_a$, that conduction to the display area is more rapid in auditory channels than in visual channels. If this is true, then if one wishes to present an auditory signal and a visual signal in such a temporal relation that the messages arrive in the display areas simultaneously, it would be necessary to have the light precede the sound by some duration which we will call x. This quantity, x, must, of course, equal the difference between the conduction delays in the two channels or

$$x = d_v - d_a.$$

So defined, x is likely to be a positive number.

Therefore, x is the amount of time by which a light signal must precede a sound signal in order for the corresponding messages to reach the display areas simultaneously. When such an event occurs, it is impossible for attention to be directed at each of the channels at the moment the messages arrive in the channels and at least one of the messages must be delayed by the attention mechanism.

The value of x is not assumed to be fixed. It is obvious that it may be different if the nature of the stimulus signal is changed. For example, $d_v$ and $d_a$ are undoubtedly functions of signal intensity, retinal position and many other externally manipulable factors. One is tempted to accept the assumption, however, that x is fixed for a particular light and a particular sound under constant stimulus conditions. But even that assumption need not be made. The quantity x will be treated as a theoretical parameter which may take different values even under constant stimulus conditions.

The models also assume that the attention mechanism to some extent is under the control of external factors such as instructions with respect to the channel which will be scanned or attended. This is indicated also in Figure 1.

## The Scanning Model

One possibility is that the switching of attention from one channel to another is regulated by a periodic source within the brain and that switching can occur only at regularly spaced points in time. There is no direct evidence to support this conjecture, but neither is it an entirely random guess. Periodic fluctuations in voltage are a salient feature of observable cerebal activity and, while little is known of the psychological significance of these brain rhythms, it is generally agreed that at least one of them, the alpha rhythm, appears predominately on the afferent side and somehow is involved in acts of attention. Several authors have speculated that alpha, with a period of approximately 100 milliseconds, is a manifestation of a sensory gating mechanism (Pitts and McCulloch, 1947; McReynolds, 1953; Stroud, 1949).

Such a mechanism is postulated as a specific value of assumption 4 to define the model which will be called the scanning model. The attention mechanism is hypothesized to be controlled by a periodic generator in such a way that attention can switch between channels only at one point in time during each period. The period of the generator, M msec. in duration, is internally determined; it is independent of sensory input. It is also assumed to be a fixed value, at least under constant conditions.

Thus, attention can change direction at most once every M msec. However, it may remain in one location for multiples of M msec.

This means that the time which must elapse before a stepwise signal can be processed will be lengthened, on the average, and its variability will be increased, when attention is directed at some other channel when the signal arrives compared to when it is directed at the channel which contains the signal. For any particular trial on which attention must switch before the message can be gated, the amount of delay added by the switching mechanism will be any value from zero to M msec., depending upon the point within a period at which the signal to switch is received. The distribution of switching times will be rectangular, all values from 0 to M being equally likely, and it will have a mean of M/2 and a variance of $M^2/12$.

There are aspects of the preceding discussion which need further clarification. Let $t_d$ be the time of arrival of a message in the display area and $t_p$ be the time of arrival of the message at some arbitrary point in the pathway through and beyond the attention mechanism. The time required for the message to travel from d to p, when attention is directed at d at time $t_d$, will be

$$t(d,p)_{on} = t_p - t_d.$$

When attention is directed at a channel other than d at time $t_d$, the value of t(d,p) will be

$$t(d,p)_{off} = t(d,p)_{on} + \delta + t_{ss} + t_s,$$

in which $\delta$ = delay due to the period of the switching mechanism:

$t_{ss}$ = time required for switching signal to travel from display area to switching mechanism; and

$t_s$ = time required to complete the switching operation once it has started.

Thus, the distribution of delays which are added when attention is misaligned consists of measures which are the sum of $\delta, t_{ss}$ and $t_s$. If $t_{ss}$ and $t_s$ are constants, then obtained delay distributions should extend from $(t_{ss}+t_s)$ to $(t_{ss}+t_s+M)$ and should have a mean of $(t_{ss}+t_s+M/2)$ and a variance of $M^2/12$.

Fully recognizing that it is only approximately true, it will be assumed that the sum of $t_{ss}$ and $t_s$ is sufficiently small with respect to M to allow it to be neglected. If $(t_{ss}+t_s)$ is of appreciable magnitude, and if it is a constant value, then estimates of the parameter M based upon the means of data distributions will be spuriously large while estimates based upon obtained variances will not be biased.

## The Fixed Switching Time Model

The scanning model asserts that attention can switch channels only at certain points in time and that the spacing of these points is determined by an internal rhythm. A simpler view, and one which might seem more reasonable *a priori*, is that attention can switch whenever the mechanism is signalled to do so and that the time required to switch to a new channel is a constant.

For this "fixed switching time" model, assumption 4 becomes: when attention is not directed at channel A and a signal from channel A notifies the mechanism to switch to channel A, a fixed interval of time, $\Delta$, is required to accomplish the switching.

## THE THEORY APPLIED TO SUCCESSIVENESS DISCRIMINATION

If two events occur simultaneously in separate sensory channels, their occurrence must be registered successively after passing the attention mechanism since only one of them can be gated at a time. And, if the two events occur successively, the fact of their successiveness can be known only if information of the non-occurrence of one follows a message which says that the other has occurred. For this to happen, it is necessary for the events to be separated sufficiently in time for attention to switch channels at least once during the interval between them. Hence, the ability to discriminate two <u>independent</u> sensory events as successive rather than simultaneous is limited by the time required to switch attention from one channel to another; and, conversely, by measuring this ability, under carefully specified conditions, we can infer values for the switching time parameter.

One way of making such a measurement is to use a two-choice forced-choice psychophysical method in which each trial consists of two visual-auditory pairs which are presented one after the other. The observer is asked to indicate the pair in which the termination of the signals occurred successively. One of the pairs is the same on all trials and is designed so that it is always judged to have simultanerus signal offsets. It is called the standard. The second pair on each trial, the variable, may have any one of several time intervals separating the offset of the light from that of the sound. The longer this interval, the greater is the probability that the variable will be chosen as the successive pair. This probability, P(C), is measured as a function of the variable interval.

Stimulus terminations are used as the critical events so that both stimuli will be present during the time immediately preceding the relevant signals. This is important because their presence defines the two sensory channels which are the relevant ones as unequivocally as possible for the subject, thereby increasing the likelihood that he will attend to one or the other, and not to some irrelevant channel.

These stimulus events are depicted in Figure 2. The two offsets are shown as occurring simultaneously for the standard pair, while the light offset precedes the sound by an interval of t msec. in the variable pair.

One would not expect the temporal relations in Figure 2 to be preserved in the neural display areas because an appreciable duration is required for the transmission of the stimulus information over the projection pathways to the display areas and because this afferent delay is probably different for different channels. This delay is usually less in an auditory channel than in a visual channel and this fact is incorporated into Figure 3, which shows the effect of such a transformation upon the stimulus events of Figure 2.

While the stimulus events can be represented fairly as stepwise changes, such is not the case with the neural events which they produce. A step change in a stimulus produces a pattern of excitation in the display areas which is widely dispersed in time. The square waves of neural excitation in Figure 3 are not intended to describe this. They merely indicate whether the excitation at each moment is sufficient or insufficient to indicate the presence of the corresponding signal.

The effect of the difference in conduction time between the two channels is to change the temporal relations between the offsets for both the standard and the variable. The standard is no longer simultaneous; instead, the auditory event precedes the visual by an interval $T_s$. And for the variable, the interval t is reduced to $T_v$. The amount of

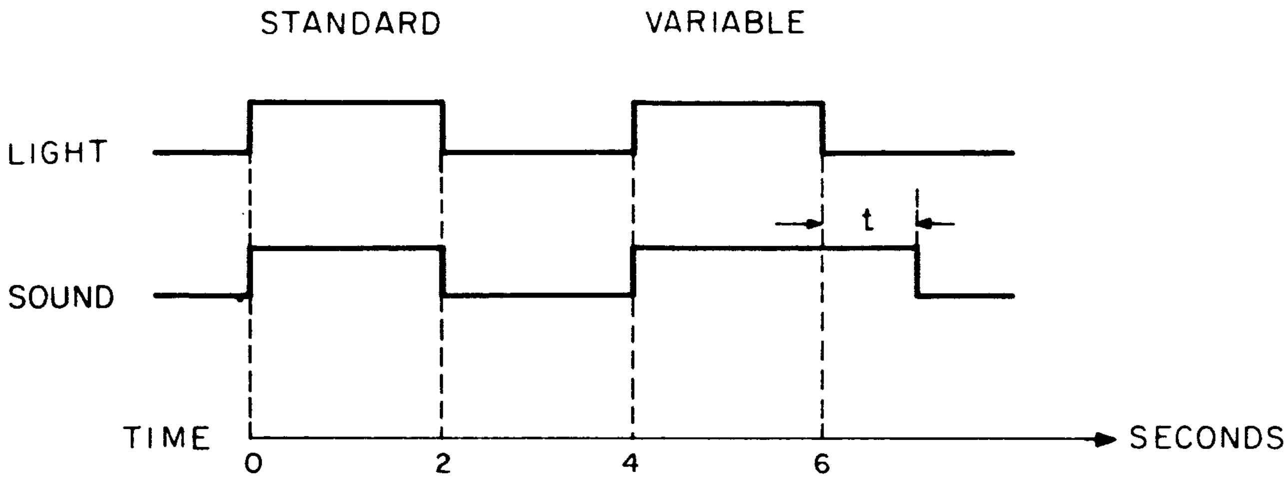

FIG. 2 DIAGRAM OF STIMULUS EVENTS IN ONE FORCED-CHOICE TRIAL. ON ONE-HALF OF THE TRIALS, SELECTED RANDOMLY, THE STANDARD FOLLOWS THE VARIABLE.

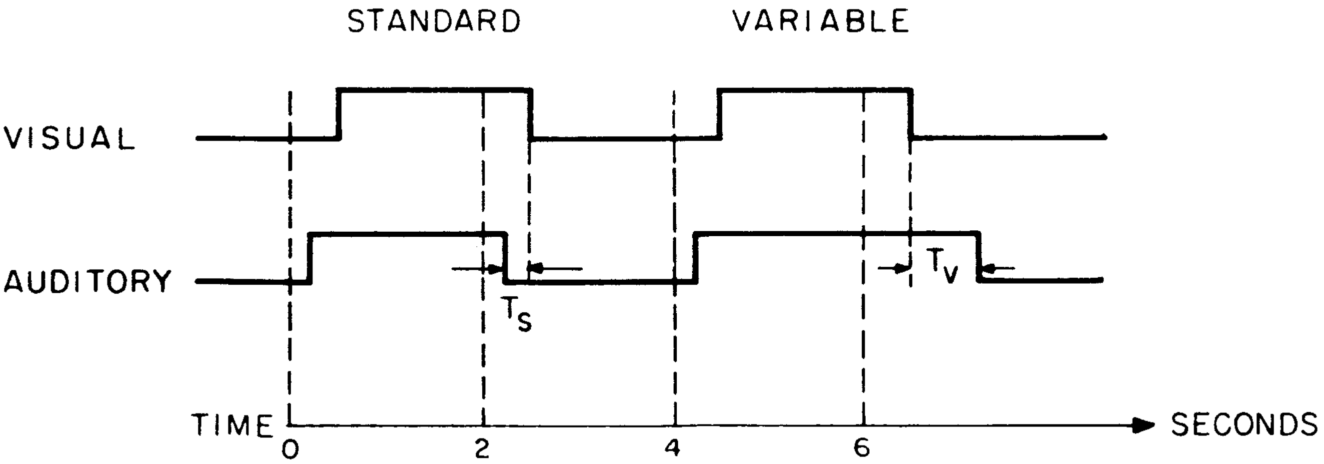

FIG. 3 DIAGRAM OF HYPOTHETICAL NEURAL EVENTS CORRESPONDING TO THE TRIAL OF FIG. 2. THE TIME LINE IS IDENTICAL TO THAT OF FIG. 2.

change in both cases is, of course, x - the difference in conduction time between the two channels.

Discrimination is based upon the information contained in the neural events, not the stimulus events. Therefore, if we wish to present two pairs of signals, of which one is a standard in which the offsets are truly simultaneous, then we must adjust the offset asynchrony of the standard to compensate for the conduction time difference. If we choose a standard in which the light offset precedes the sound offset by exactly x msec., then the offsets of the neural events will be simultaneous (to the extent that x is constant). But the value of x is not known and cannot be measured with any precision with the techniques which are available. Fortunately, it may not be necessary for the standard interval to be exactly x, for reasons that will be explained shortly.

For the moment, suppose that the standard interval is x and that the neural events produced by the standard are simultaneous. Even when this is the case, the information that one of the offsets has occurred cannot become available to the subject at the same time that the same information becomes available about the other offset. That is, if the subject is attending to the visual channel when the simultaneous offsets occur, he can, at best, observe first the visual offset and then later, upon switching to the auditory channel, observe that the auditory offset has occurred.

In order for him to discriminate the two neural events as successive, it must be possible for him to observe that one event has occurred and then to switch his attention to the other channel in time to observe that the second event has not yet occurred. Even if the events are, in fact, successive, if he does not observe the absence of one after having observed the presence of the other, the result is the same as it would have been if the events had been simultaneous. Therefore, <u>successive independent neural events which do not differ in time enough to allow attention to switch channels between them are equivalent to simultaneous events</u>. This assertion contains the implicit assumption that, if on switching to a channel an event is found to exist there, no information is contained in the channel which indicates how long the event has been there. Or, the only temporal information available to the subject is that which he can derive from knowing whether an event exists or does not exist at a particular instant when it is being attended. Independent afferent neural events can be given relative "dates" only by an action of the attention mechanism.

Two events, then, can be discriminated as successive only if they are separated by more than the time required to switch attention from one channel to the other. And they will be so discriminated only if the order of observing the channels is such as to observe the occurrence of one event followed by the observance of non-occurrence of the other. This latter requirement makes it clear that the identity of the channel which is being attended at the instant the first event occurs is another determiner of whether the events are seen as successive.

For example, suppose the two events are separated sufficiently in time to allow attention to switch once in the interval between them. If attention is directed at the channel which contains the first event, then that event will be observed and attention can switch to the other channel in time to register the later occurrence of the second event. If, on the other hand, attention is directed at the channel of the second event when the first occurs, it may be signalled to switch to the channel of the first event, by the first event, but there will be insufficient time for it to switch a second time to pick up the non-occurrence of the second event. Therefore, if the channel of the second of two successive events is being attended when the first event occurs, the two events must be separated by an interval equal to or greater than two attention switching times if they are to be discriminated as successive. A similar argument can be made for the case in which attention is directed at some third channel at the moment the first event occurs.

## Derivation for the Scanning Model

Now we will consider this within the framework of the scanning model which assumes that attention can switch channels only once every M msec. Assume further, for the present, that the subject always attends to the visual channel when the first of the two events in a visual-auditory pair occurs (i. e. $P_\ell$=1.0). If the standard pair consists of a light offset which precedes the sound offset by x msec., the two neural events will always be simultaneous and if the subject is asked to compare a variable pair having an interval of x with such a standard, he will perform at a chance level. i.e. P(C)=.50. If the variable interval exceeds x, that is, if the visual neural event occurs before the auditory, the variable will be discriminated as successive whenever a switching point falls between the two neural offsets. One switching point is sufficient because $P_\ell$=1.0. The probability that the two neural events will occur with respect to the scanning period in such a way as to bracket a switching point will be a function of their time separation. If they are M or more milliseconds apart, *i.e.* if the variable interval is (x+M) or more, then no matter where the first event falls within the period of the scanner, the second event must fall in the next, or a later period. Hence, if the variable interval is (x+M) or greater, the variable will always be coded as successive, the standard will always be simultaneous, and P(C)=1.0. Similarly, since the point within a scanning period at which the first event will occur is a matter of chance, the probability that the two events of the variable will fall with a switching point between them will be directly proportional to the variable interval, being zero when the interval equals x and increasing linearly to 1.00 when it equals x+M.

This relationship is shown as the ascending line on the right side of Figure 4. The baseline of this figure is the variable interval. Positive values mean that the light offset precedes the sound; negative values mean the reverse.

If the variable interval is any value between x and (x-M), then the neural event in the auditory channel will occur first by an interval between 0 and M msec. For all

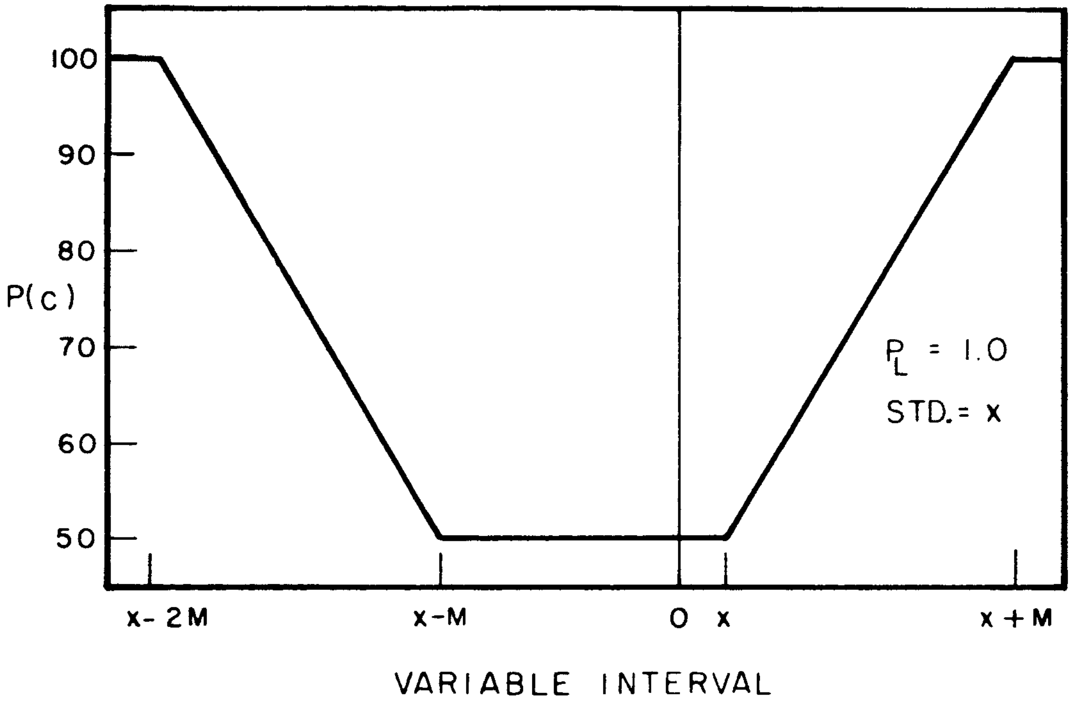

FIG. 4 RELATIONSHIP EXPECTED BY THE SCANNING MODEL BETWEEN THE PROBABILITY OF DESIGNATING THE VARIABLE AS SUCCESSIVE AND THE INTERVAL BETWEEN THE OFFSETS OF THE VARIABLE PAIR.

such intervals, there can occur no more than one switching point between the two events. But since $P_\ell$=1.0, two switching points are necessary if the events are to be discriminated as successive. Hence, for all values of the variable interval within this range, P(C) will be .50.

Finally, if the sound precedes the light by more than (x-M) msec., the probability that the required double switch can occur will be greater than zero. By the same argument as above, this probability will increase linearly from .50 at (x-M) to 1.0 at (x-2M).

The main requirement for the standard interval is that it be indistinguishable from an interval equal to x on every trial. This derivation has shown this to be true of any interval between (x-M) and x. Hence, we are released from the need to determine x exactly in order to construct the standard pair. It is sufficient that the standard have any interval less than x by an amount not greater than M. But note that this is true only for this special case in which $P_\ell$ is assumed to be unity and it is important to design experimental conditions in such a way as to make $P_\ell$ close to one if we wish to take advantage of this simplest case to measure the parameters x and M.

In order to maximize $P_\ell$, *i.e.* to assure that the subject will attend to the visual channel at the appropriate time when each pair is presented, it is probably necessary for the subject to have the expectation that the first event will be in the visual channel. He would maximize P(C) by always attending to the visual channel only if all first events are in that channel. Therefore, Figure 4 in its totality does not describe a feasible case to use for measurement. One would not want to present negative values of the variable interval.

The simplest case, and the one which would seem to have the greatest chance of yielding data consistent with the model, is the one in which:

1. The standard is less than x by not more than M.

and

2. Only positive values of the variable interval are presented, and the subject is asked to identify the pair in which the light offset precedes the sound, rather than to identify the successive pair.

For this case, the prediction is given in Figure 4 as the right half of the graph. Fitting a straight line to obtained values of P(C) permit one to calculate x and M. One test of the scanning model lies in the form of the data: the model expects linearity.

Figure 4 portrays the result to be expected for an "ideal" subject. To match the ideal, a subject must not only maintain attention on the visual channel 100 percent of the time, but he must also switch attention to the auditory channel at the earliest possible time after the visual event occurs and he must do so with complete reliability. If there is some probability $P_f$ that he fails to switch at the end of the scanning period immediately following the visual event, and if $P_f$ is the same for each subsequent switching point, the theoretical function becomes like those in Figure 5. As $P_f$ increases, the slope of the linear segment between x and (x+M) decreases and the over-all form of the data becomes more difficult to distinguish from a curvilinear hypothesis.

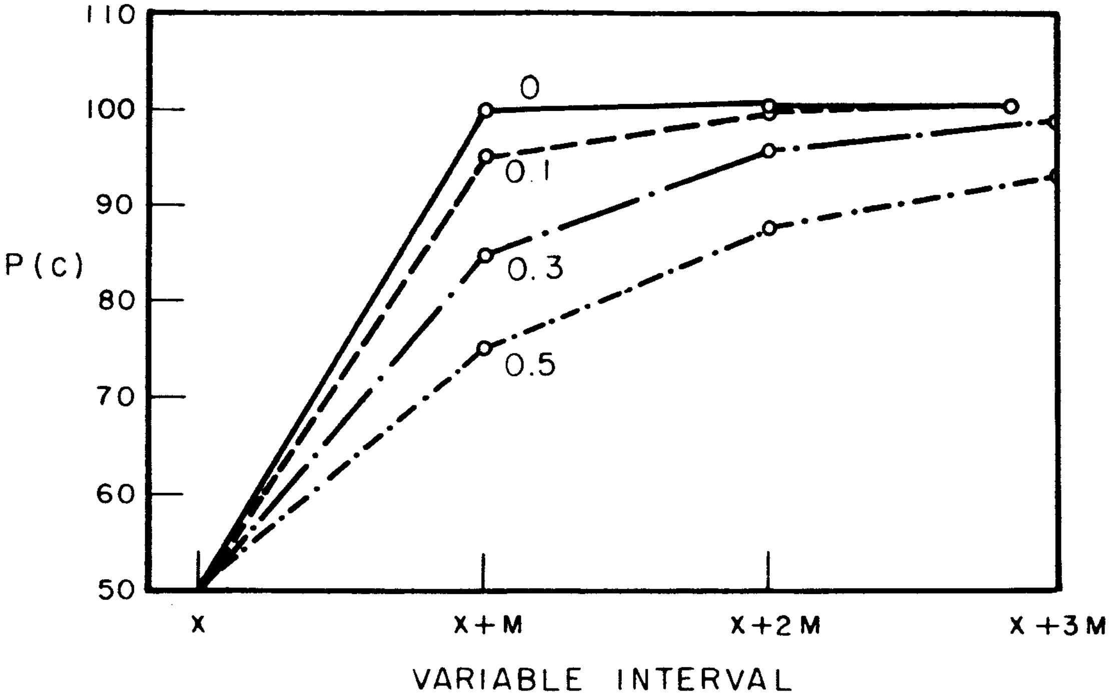

FIG. 5 THE INFLUENCE OF UNRELIABLE SWITCHING UPON THE SUCCESSIVENESS DISCRIMINATION FUNCTION. THE PARAMETER IS $P_f$, THE PROBABILITY OF FAILING TO SWITCH AT EACH POSSIBLE SWITCHING POINT.

## Derivation for the Fixed Switching Time Model

It should be easy to see now that the fixed switching time model would expect the successiveness function to be a step function. If the time required to switch attention were constant and equal to $\Delta$ msec., then values of the variable interval greater than $x+\Delta$ would yield 100% correct responses, values of the interval between $(x+\Delta)$ and $(x-2\Delta)$ would yield chance performance, and intervals less than $(x-2\Delta)$ would again give 100% correct. Thus, again, assumes that $P_\ell=1.0$.

One particular failure of an actual subject to match the ideal of this model would generate an interesting successiveness function. If the mechanism were unreliable in the sense that it sometimes failed to find a channel to which it had been ordered to switch and needed a second, or third, or more, try before locating it, the function relating P(C) and the variable interval would be an ascending staircase with the first upward step occurring at $(x+\Delta)$ and subsequent steps at $(x+2\Delta)$, $(x+3\Delta)$, etc.

## THE THEORY APPLIED TO CHANNEL UNCERTAINTY IN REACTION TIME

The previous section developed a way of coordinating the theory of attention to certain psychophysical data. Probability values constitute the actual obtained data, and the theoretical parameters are inferred from certain relations between these probabilities and aspects of the stimulus signals.

This section will show how the theoretical parameters might be measured in what seems to be a more direct manner. By measuring reaction time, i.e., the time which elapses between an input signal and a response, it should be possible to determine the temporal parameters of attention switching by comparing reaction times on occasions when attention is directed at the channel containing the signal to reaction times on occasions when attention must switch before the signal can be gated.

In the typical simple reaction time experiment the subject is given full information about the signal and he also knows exactly, in advance of each trial, the response which he will make. Under these conditions, particularly if the termination of the stimulus is the signal to respond so that the relevant channel is well-defined for the subject, it may be the case that the probability that the subject will attend to the relevant channel at the critical moment will be nearly unity. For an ideal subject, we assume that it is unity, or that the probability that attention will be "misaligned," $P_m$, is zero.

Under these conditions simple reaction times, a set of values of t, are obtained which have a mean of $\bar{t}$ and a variability of $\sigma_t^2$.

If conditions are less than ideal so that $P_m$ is not zero, then on those trials on which attention is misaligned, an additional delay, $\delta$, will be added to t. The quantity $\delta$ is, as before, the time required for attention to switch to the relevant channel. For this statement to be useful it is necessary to find conditions of misalignment which have no influence upon t other than $\delta$.

If the distribution of t can be measured (i.e., $P_m=0$) and if a distribution of T can be obtained, in which the values are reaction times taken when $P_m$ is some value greater than zero, then certain characteristics of the switching time of attention can be inferred by comparing the two distributions. For example, the mean of the T-distribution will be:

$$\bar{T} = \bar{t} + P_m \Delta \qquad (1)$$

in which $\bar{t}$ is the mean of the t-distribution and $\Delta$ is the mean of the distribution of attention switching times (the $\delta$-distribution).

If the value of $P_m$ can be measured or assumed, one can then calculate $\Delta$ from equation (1).

Also, the variance of the T-distribution will be:

$$\sigma_T^2 = \sigma_t^2 + P_m \sigma_\delta^2 + \frac{(1 - P_m)}{P_m}(\bar{T} - \bar{t})^2 \qquad (2)$$

which contains only $P_m$ and measurable quantities in addition to $\sigma_\delta^2$, the variance of the hypothetical switching time distribution. And again, if $P_m$ were known, $\sigma_\delta^2$ could be calculated from the two sets of reaction time data.

Equations (1) and (2) express the effect upon the mean and upon the variance of a distribution of adding a variable quantity to some, but not all, of the members of the distribution. It assumes that T will be the same as t on $(1-P_m)$ of the trials on which T is measured.

It would be most desirable to measure $P_m$ and then apply the equations. Unfortunately, that cannot be done and some alternative method of handling $P_m$ must be found.

One way to bring $P_m$ under control is to introduce uncertainty as to channel into the simple reaction time experiment. The minimal change in the simple reaction time procedure which will accomplish this is to add a second well-defined channel while changing no other aspect of the procedure.

As in the previous section, the following discussion will center around the two-channel visual-auditory case in which stimulus offsets are the signals. For this two-channel case, four reaction time distributions may be defined:

| Distribution | Signal | Knowledge of Channel | Mean | Variance |
|---|---|---|---|---|
| $t_\ell$ | light | certain | $\bar{t}_\ell$ | $\sigma^2_{t_\ell}$ |
| $t_s$ | sound | certain | $\bar{t}_s$ | $\sigma^2_{t_s}$ |
| $T_\ell$ | light | uncertain | $\bar{T}_\ell$ | $\sigma^2_{T_\ell}$ |
| $T_s$ | sound | uncertain | $\bar{T}_s$ | $\sigma^2_{T_s}$ |

When the subject is certain of the channel over which the next signal will arrive, it is assumed that he will attend to that channel with a probability of one ($P_\ell$=1 or $P_s$=1). When he is uncertain, he knows that the next signal will arrive over either channel $\ell$ or channel s. Thus, the probability that attention will be misaligned on any trial will be a minimum of .50, regardless of the probability with which the subject attends to each channel, providing the two kinds of signals occur randomly and equally often. The minimum misalignment probability exists when the subject attends to either one or the other of the two channels and never elsewhere (i.e., when $P_\ell + P_s = 1$). In general, the over-all probability of misalignment under uncertainty will be:

$$P_m = 1 - \frac{(P_\ell + P_s)}{2}$$

It must be emphasized that certainty as to channel is the only difference between experimental conditions. The same, single response is required under all conditions and all other aspects of the situation are identical.

To simplify the ensuing discussion, the following relations among data are defined:

$$a = \bar{T}_{\ell} - \bar{t}_{\ell}$$

$$b = \bar{T}_{s} - \bar{t}_{s}$$

$$c = \sigma^2_{T_{\ell}} - \sigma^2_{t_{\ell}}$$

$$d = \sigma^2_{T_{s}} - \sigma^2_{t_{s}}.$$

The quantities (a) and (b) are the measured effects of uncertainty upon the mean reaction time in the light and sound channels, respectively and (c) and (d) are the increments in variance attributable to uncertainty. In these terms, an equation (1) and an equation (2) can be written for each channel:

$$P_{m\ell}\Delta = a \tag{3}$$

$$P_{ms}\Delta = b \tag{4}$$

$$P_{m\ell}\sigma_\delta^2 + a^2\left(\frac{1 - P_{m\ell}}{P_{m\ell}}\right) = c \qquad (5)$$

$$P_{ms}\sigma_\delta^2 + b^2\left(\frac{1 - P_{ms}}{P_{ms}}\right) = d. \qquad (6)$$

These four equations contain four unknowns: $\Delta$, the mean switching time; $\sigma_\delta^2$, the variance of switching times; $P_{m\ell}$, the probability of not attending to channel $\ell$ under uncertainty; and $P_{ms}$, the probability of not attending to channel s under uncertainty. Of course, $P_{m\ell}=(1-P_\ell)$ and $P_{ms}=(1-P_s)$.

The theory postulates an attention switching mechanism which is independent of sensory modality. Hence, the parameters of the $\delta$-distribution are the same in both directions between the two channels.

Solving equations (3) and (5) for $\sigma_\delta^2$ in terms of $\Delta$ gives:

$$\sigma_\delta^2 = \Delta\left(\frac{c}{a} + a\right) - \Delta^2. \qquad (7)$$

This relation is independent of the form of the $\delta$-distribution and holds for any value of $P_{m\ell}$. It permits comparisons to be made between successiveness discrimination data and reaction time data. For example, if successiveness data were described by a normal ogive, the relationship between the mean and the variance of the ogive would be expected to agree with the relationship expressed in (7). This is one very general way in which the data of one kind of experiment can be predicted, quantitatively, from that of the other kind.

Since an equation analogous to (7) can also be written for channel s, it follows that:

$$\frac{c}{a} + a = \frac{d}{b} + b \qquad (8)$$

Equation (8) shows that the effect of uncertainty upon mean reaction time, added to the ratio of the effect upon variances to that upon means, must be the same for all channels if the general assumptions of the theory are correct. If a method of deciding when the two sides of equation (8) are unequal can be found, it will provide a very powerful test of theory.

It can be shown that there is no unique solution for the system of equations (3),(4),(5),and (6). For any set of values for a, b, c, and d which satisfy (8), there exists a different set of values for $P_{m\ell}$, $P_{ms}$, and $\sigma_\delta^2$ which satisfy the system of equations for each possible value of $\Delta$.

However, the system of equations does allow one to calculate the range of possible meaningful values of the parameters for any set of data. Since $\Delta$ and $\sigma_\delta^2$ cannot be negative and since $P_{m\ell}$ and $P_{ms}$ must each be between zero and one and their sum between one and two, it follows from equations (3) to (6) that

$$\Delta_{max} = \text{the lesser of } \frac{c + a^2}{a} \text{ or } (a + b)$$

and

$$\Delta_{min} = \text{the greater of a or b.}$$

An additional assumption is required if the system of equations is to yield unique solutions for the theoretical parameters. Several alternatives will be discussed next.

### Assuming $P_\ell + P_s = 1$

If it is assumed that the subject attends to one or the other of the two relevant channels and not elsewhere when he is uncertain which of the two will contain the next signal, a solution can be found. This assumption, that $P_\ell + P_s = 1$, is equivalent to assuming that

$$P_{m\ell} + P_{ms} = 1$$

since $P_{m\ell} = 1 - P_\ell$ and $P_{ms} = 1 - P_s$.

With this addition, the system of equations gives the following solution for the four theoretical parameters:

$$\Delta = a + b \tag{9}$$

$$\sigma_\delta^2 = \left(\frac{c}{a} - b\right)(a + b) \tag{10}$$

$$P_{m\ell} = \frac{a}{a + b} \tag{11}$$

$$P_{ms} = \frac{b}{a + b} \tag{12}$$

Therefore, the mean and variance of the switching time distribution as well as $P_\ell$ and $P_s$ can be calculated without assuming a specific form for the distribution.

### Assuming a Rectangular $\delta$-Distribution

The central assumption of the scanning model described above is that the switching time is equally likely to be any value from zero to M msec. The $\delta$-distribution, thus, has a specific relationship prescribed between $\Delta$ and $\sigma_\delta^2$:

$$\Delta = \frac{M}{2}$$

$$\sigma_\delta^2 = \frac{M^2}{12}$$

or,

$$\sigma_\delta^2 = \frac{\Delta^2}{3}$$

This relationship, in combination with equations (3) to (6), provides the following solution for channel $\ell$:

$$\Delta = \frac{3\ (c + a^2)}{4a} \qquad (13)$$

$$\sigma_\delta^2 = \frac{3\ (c + a^2)^2}{16a^2} \qquad (14)$$

$$P_{m\ell} = \frac{4a^2}{3\ (c + a^2)} \qquad (15)$$

Thus, it is possible to estimate the switching time parameters from the reaction time data for channel $\ell$ alone, along with the probability that the subject failed to attend to that channel at the critical instant. Analogous equations can be written for channel s, of course, which means that two estimates of $\Delta$ and $\sigma_\delta^2$ can be obtained from the data of one experiment and that the adequacy of the theory can be assessed by comparing them. Note that no assumption is made which restricts the values of $P_\ell$ and $P_s$; instead, they each can be calculated. And, of course, the period of the postulated scanning mechanism can be calculated once $\Delta$ is known.

Assuming $\sigma_\delta^2 = 0$

This extreme assumption, that the switching time is the same on all trials, leads to:

$$\Delta = \frac{c + a^2}{a} \tag{16}$$

$$P_{m\ell} = \frac{a^2}{c + a^2} \tag{17}$$

And, again, $\Delta$ can be calculated independently for channel s, along with $P_{ms}$.

## Derivation for the Scanning Model

In the analyses of reaction time experiments the term "scanning model" will designate a particular combination of the assumptions which have been discussed in the previous paragraphs. While it relies upon a greater number of assumptions than any of the preceding methods of analysis, it provides yet another way of considering the data.

Specifically, the scanning model assumes the rectangular form for the $\delta$-distribution, as it has in the earlier discussion. It also assumes that $P_\ell + P_s = 1$. Each of these assumptions is described separately above and each is shown to be sufficient to permit some calculations. If both assumptions are accepted, it becomes possible to calculate two full sets of theoretical parameters from the reaction time data alone, one set from the means of the four distributions and a second set from the variances. These can then be compared to each other and best estimates, based upon both if they do not differ, can be compared to those obtained from successiveness discrimination data.

Using equations (3) and (4) with $P_{m\ell}=P_s$ and $P_{ms}=P_\ell$, since it is assumed that $P_\ell+P_s=1$, the mean switching time is seen to be:

$$\Delta = a + b. \tag{18}$$

This, of course, is the same as equation (9).
Also,

$$P_\ell = 1 - P_s = \frac{b}{a + b} \tag{19}$$

and, since $\Delta=M/2$ and $\sigma_\delta^2=M^2/12$, it follows from (18) that

$$M = 2\ (a + b) \tag{20}$$

and $$\sigma_\delta^2 = \frac{(a + b)^2}{3} \tag{21}$$

Equations (19), (20), and 21 allow one to estimate all parameters from the measured effects of uncertainty upon reaction time means.

The two assumptions in combination with equations (5) and (6) permit the following variance relations to be deduced:

$$c = P_s M^2 \left(\frac{1}{3} - \frac{P_s}{4}\right) \tag{22}$$

$$d = P_\ell M^2 \left(\frac{1}{3} - \frac{P_\ell}{4}\right) \tag{23}$$

Since all of the quantities on the right sides of equations (22) and (23) can be calculated from the means of the obtained distributions using equations (19) and (20), one approach is to calculate predicted values of c and d and compare them with obtained values. It would be entirely equivalent to calculate predicted values for $\sigma^2_{T_\ell}$ and $\sigma^2_{T_s}$ to compare with the measured values since, <u>e.g.</u>, $\sigma^2_{T_\ell} = c + \sigma^2_{t_\ell}$.

Equations (22) and (23) show that the increase in reaction time variance which is produced by channel uncertainty is directly proportional to $M^2$ and non-monotonically related to P, being maximum when P=.67, zero when P=0, and $M^2/12$ when P=1.

A third method, which is logically equivalent, is to calculate separate estimates of the theoretical parameters from the measured variances alone. From equations (22) and (23):

$$P_\ell = 1 - P_s = \frac{-\,(4 - \frac{2d}{c} \pm \sqrt{(4 - \frac{2d}{c})^2 + 12\,\frac{d}{c}\,(\frac{d}{c} - 1)}}{6(\frac{d}{c} - 1)} \qquad (24)$$

$$M^2 = \frac{12d}{4P_\ell - 3P_\ell^{\,2}} \qquad (25)$$

## Derivation for the Fixed Switching Time Model

This model assumes that $\sigma_\delta^2=0$. If it is further assumed that $P_\ell+P_s=1$ under uncertainty, then the fixed switching time calculated from the means of the four distributions is:

$$\Delta = a + b, \tag{26}$$

and the variance relations are:

$$c = P_\ell P_s \Delta^2 \tag{27}$$

$$d = P_\ell P_s \Delta^2. \tag{28}$$

Therefore, this model can be tested experimentally by comparing observed and predicted values of the increment in variance due to channel uncertainty. The model expects this increment to depend upon $P_\ell$ and $P_s$, but to be the same for the two channels for any pair of $P_\ell$ and $P_s$ values.

## PLAN OF EXPERIMENTS

The rationale developed in the previous sections details two independent ways to investigate certain aspects of attention, one through the measurement of reaction time and the second through the measurement of the discrimination of successive from simultaneous pairs of signals. Each of these measurements yields internal comparisons which test and mold the theory. Each also yields estimates of the same theoretical parameters.

Accordingly, the general plan for work in the laboratory is to perform both sets of measurements and to use the data to decide whether the general theoretical approach is promising and, if it is, to sharpen the theory by excluding inadequate models of it. A particular model is adequate to the extent that it (a) predicts the form of successiveness functions, (b) predicts the interrelations among reaction time statistics, and (c) yields the same estimates of the theoretical parameters from the two kinds of measurement.

Since (a) the theory is quantitative and (b) there is no reason to believe that the parameters are the same for different individuals, and (c) the theory does not explain individual differences, it would be inappropriate to combine data for different individuals. Therefore, single individuals will be studied intensively, enough data of both kinds being obtained on each subject to make it possible to perform all of the analyses. A large enough number of subjects will be used to provide some notion of the extent of individual differences in the major parameters and to ensure generality for conclusions about the adequacy of the theory.

In the experiments which follow, data are presented for sixteen male subjects between the ages of 17 and 20. For every subject reaction time measurements were made first over a period of many days and the results are given as Experiment 4. Then, in Experiment 5, the successiveness discrimination procedure was begun and carried out for a number of days. In no case were the two kinds of experiments conducted with the same subject during the same period of time. One day's session lasted about one hour, including rest periods. The subjects were paid for their time. Every subject who began an experiment endured for the entire series.

Some of the same subjects took part in Experiments 1, 2 and 3, which were preliminary studies which led to the development of the procedures for Experiment 4, and in Experiment 6 which introduced a further modification in that procedure.

## APPARATUS

The visual and auditory signals were identical for all experiments, a 2,000 cps tone of moderate loudness and a uniform circular spot of light directly fixated by the subject. The tone was delivered over headphones. The visual target consisted of the front plate of an NE-40 neon lamp, powered by 85 v.d.c., and viewed within a black box at a distance of 34 inches. The spot subtended about 1.8 degrees of visual angle. Stimulus offsets were the effective signals.

In other respects the subject's environment was the same for all experiments. He sat at a table in a separate sound-deadened room with the room lights on and with freedom to look about between trials. A separate sound source served variously as a ready signal, as a pre-trial instructional cue, and as a source of knowledge of results.

Trials were presented by an experimenter in an adjoining room. Each trial was pre-programmed and controlled by an apparatus constructed of digital computer components. This apparatus presents, in a single cycle of operation, up to nine immediately successive time intervals. The nine intervals can each be selected from among five independent timing circuits. During each interval any combination of four stimulus outputs can be gated. The sequence of intervals and outputs is pre-programmed by inserting diodes into a plug board on the front of the unit.

A two-kilocycle master source controls all timing functions and also provides the auditory signal. All output gating is synchronized to this source and the point on the cycle at which gating occurs can be preset so that, for example, all gating can be done at zero-crossing to minimize clicks. Time intervals of multiples of .0005 second can be generated.

The same equipment also operates in a reaction time mode to present the signals and display reaction times to the nearest .0005 second.

The programming of trials and data recording were done manually.

# EXPERIMENT 1

## DETECTION REACTION TIMES MEASURED IN SEPARATE SERIES

This experiment was designed to determine the influence of channel uncertainty upon reaction time. Since it was realized that the direction of attention on each trial is extremely important, particularly that $P_\ell=P_s=1$ is an assumption which must be met under the condition of certainty, it was decided to begin by measuring reaction time for each condition separately, finishing one condition before beginning another. Such a procedure does not require the subject to learn and maintain during the same time period attitudes of attending which are optimal for each condition. Instead, he can learn and use a single attitude and then discard it when it becomes appropriate to learn another. Such an approach, however, must assume that there are no important long-term changes in reaction time which can affect the different conditions differentially.

Reaction time to the visual signal with certainty was measured first on each of 13 days, followed by a number of days devoted to the auditory signal with certainty. Then, several days were spent determining reaction times under uncertainty. It was expected that there would be practice effects for each of the three conditions and that sufficient data would have to be obtained in each case, after systematic day-to-day changes ceased, to determine each of the statistics with sufficient stability.

Only one subject, J. C., was used. On the first thirteen days, $t_\ell$ was measured, followed by ten days for $t_s$. Then, five days for $T_\ell$ and $T_s$ together completed the experiment.

At the beginning of a trial the experimenter signalled the subject to start. The subject initiated the trial by depressing a key and holding it down with his preferred hand. Depressing the key activated both the light and the sound and, at the end of a preset foreperiod, one of the stimuli would terminate and the subject would respond by releasing the key.

The same, single response was used under all conditions and the procedure was identical under all conditions except that on all trials the subject knew exactly which signal would occur when $t_\ell$ and $t_s$ were measured. In the third condition, he knew only that either the light or the sound would terminate at the end of the foreperiod, but not which one.

A randomly selected 25 percent of all trials were catch trials on which both signals continued for several seconds beyond the foreperiod, terminating together. The subject was instructed to withhold his response on such trials. The foreperiod varied randomly, assuming any of the eleven values from 1.5 to 2.5 secs. in .1 sec. steps.

Twenty successive trials comprised a block. Either four or six blocks made up a day's session. Six blocks were used on each of the first six days, but the data showed a significant increase in reaction time during the last two blocks and the number was reduced to four from that point on.

A session, therefore, consisted of eighty trials of which twenty were catch trials. The subject was instructed to try to maximize both speed and accuracy, to release the key as rapidly as possible, but to avoid doing so on catch trials. No further definitions of speed and accuracy were given.

## Results

The first condition, $t_\ell$, required six days of practice before no further changes occurred in either the mean or the variance as a function of additional days. The first six days were discarded. The first two days of condition $t_s$

were similarly discarded. No significant changes over days could be detected in the data for the third condition and all five days were retained.

A total of twenty days, then, are available for the final analysis. On these days, a total of 400 catch trials were presented. J. C. responded on none of these trials, suggesting that he was operating at a very high criterion level and that his criterion could be different for the three experimental conditions because, if there were such differences, they could not be seen in his false-alarm rates.

The final statistics are shown in Table I. The usual large difference between means for light and sound signals is present: under certainty, the mean for the sound signal is 41 msecs. less than that for the light signal.

### Table I

Reaction Time Means and Standard Deviations

Subject J. C.

| Condition | N | Mean | Standard Deviation |
|---|---|---|---|
| $t_s$ | 369 | 176 | 21 |
| $t_\ell$ | 311 | 217 | 18 |
| $T_s$ | 107 | 173 | 15 |
| $T_\ell$ | 114 | 204 | 17 |

The expected effect of channel uncertainty is entirely absent. In fact, means and standard deviations are less under uncertainty in every case, and in one instance, the means for the auditory channel, the difference is statistically significant (t=3.7). Channel uncertainty, under the conditions of this experiment, does not increase reaction time for this subject.

## Interpretation

There seem to be some conditions under which a subject behaves as if he can attend to visual and auditory inputs simultaneously and as efficiently as he can to either channel separately. The speed with which he can respond to a signal is independent of his knowledge of the channel over which the signal will arrive.

Certain conditions prevailed during this experiment which may limit this conclusion. In the first place, the subject was thoroughly trained under the condition of certainty before any of the data were obtained upon which the conclusion is based. Uncertainty might have an effect early in practice.

Secondly, the reaction time task utilized in this experiment might be called a detection task in the sense that, under all conditions, the subject only had to detect the occurrence of a signal. There was no need for him to discriminate one signal from another. On every trial he responded to *any* sensory change, withholding his response only if no change occurred. Attention might not be necessary for detection and still be essential for discrimination.

Finally, it is conceivable that the motivational state of the subject was different under uncertainty than under certainty. The task is repetitious and boring and the addition of even minimal uncertainty might affect the subject's criterion sufficiently to override the expected effects of uncertainty. This possibility is supported by the suggestion in the data of Table I that uncertainty facilitates reaction time rather than having no effect at all.

# EXPERIMENT 2

## DETECTION REACTION TIME--ALL CONDITIONS DURING SAME TIME PERIOD

Since the two certainty conditions were completed before the uncertainty condition was begun in Experiment 1, it is possible that long-term practice effects or shifts in motivation are responsible for the slightly shorter reaction time obtained under the uncertainty condition. It is also possible that such long-term effects might have masked a small effect of uncertainty. To check these possibilities, this short experiment was conducted, using the same single subject.

In Part I of this experiment, J. C. was run under all three experimental conditions each day for four days. On each day, four blocks of twenty trials each were presented, as before. One block consisted of the sound signal with certainty, one of the light signal with certainty, and the remaining two of both signals with uncertainty. The daily order of conditions was counterbalanced over the four days so that each condition occurred equally often in each position of the order. Otherwise, all procedures were identical to those of Experiment 1.

In Part II of this experiment, J. C. participated on four additional days on each of which all three experimental conditions were presented. In this Part, the conditions were randomly intermixed from trial to trial. This was accomplished by not presenting the light at all on $t_s$ trials and by not presenting the sound on $t_\ell$ trials. Since response was to signal termination, this procedure effectively cued the subject on all certainty trials.

The main result of Experiment 1 is even more clearly seen in the data of this experiment. In Part I, there is almost no over-all change from the first experiment: the grand mean reaction time was 192 msecs. in Experiment 1 and it is 191 msecs. for Part I of Experiment 2. A data summary for Part I is given in Table II.

## Table II

Means and Standard Deviations of the Four Reaction Time Distributions for Experiment 2, Part I

Subject J. C.

| Condition | N | Mean | Standard Deviation |
|---|---|---|---|
| $t_s$ | 46 | 167 | 11 |
| $t_\ell$ | 45 | 213 | 19 |
| $T_s$ | 49 | 176 | 16 |
| $T_\ell$ | 43 | 208 | 22 |

## Table III

Means and Standard Deviations of the Four Reaction Time Distributions for Experiment 2, Part II

Subject J. C.

| Condition | N | Mean | Standard Deviation |
|---|---|---|---|
| $t_s$ | 43 | 168 | 15 |
| $t_\ell$ | 45 | 205 | 13 |
| $T_s$ | 44 | 172 | 15 |
| $T_\ell$ | 45 | 205 | 21 |

The over-all mean for Part II is 188 msecs., again insignificantly different from before. Means and standard deviations for Part II are shown in Table III.

Means were somewhat lower under uncertainty in Experiment 1. This unexpected finding is not supported by either Part of Experiment 2. All of the differences due to uncertainty in Tables II and III are sufficiently small to be regarded as trivial. Combining all three sets of data for J.C. yields a grand mean of 191 msecs. under certainty and 190 msecs. under uncertainty.

## Interpretation

For the single subject used in Experiments 1 and 2, uncertainty as to sensory channel has no influence upon reaction time. The subject was highly practiced and the task required him to respond in a single way to the detection of any change in either channel and to withhold the response when no change occurred. It should be stressed that the degree of uncertainty was minimal.

# EXPERIMENT 3

## DETECTION REACTION TIME--INCENTIVE CONTROL

This experiment is similar to the first two experiments. Using additional subjects and some degree of control over motivation, it thoroughly confirms the earlier conclusions.

Three new subjects were started through the same procedure which had been used for J. C. in Experiment 1. Each completed several days on each of which only condition $t_s$ was administered. In three of the total of four cases, $\bar{t}_s$ decreased for the first few days but thereafter increased to a somewhat higher intermediate level. Since this finding might indicate a long-range "boredom" effect, it was decided to try to control motivation by introducing a system of incentives and to complete the experiment with the same order of conditions as Experiment 1, but with the incentive control, for each of the three new subjects. J. C. was added to this experiment by running him for several additional days, first with certainty and then under uncertainty, with incentive control.

The incentive system was defined in terms of each subject's past performance with a given signal. He was told that he would receive a bonus of two cents for each response which was faster than two-thirds of his previous responses to the same signal. However, he would be penalized the same amount for every response to a catch trial and, on any one day he could not accumulate more than 75¢ in addition to his regular pay.

A second reason for introducing the incentive plan was to increase slightly the number of false alarms, i.e., positive responses to catch trials. The false-alarm rate for J. C. was zero during the first two experiments and, since a comparison of false-alarm rates between conditions can be considered an index of differences in criterion, some measurable rate is desirable.

The effects of practice and of incentive were not a primary goal of this experiment and the experiment was not designed to investigate them. They will not be discussed here except to state that the means for each subject decreased following the introduction of incentive control to a level close to that reached earlier in practice before the "boredom" effect occurred. Also, the introduction of the incentive system was followed by a small increase in false-alarm rate.

The data of interest here are those obtained under each condition after performance had levelled off following the introduction of incentive. As in Experiment 1, these data were obtained first for condition $t_s$, then $t_\ell$, and finally $T_s$ plus $T_\ell$ for each subject.

The relevant data are summarized in Table IV, which gives means and standard deviations for each condition for each subject. In collating these data, all of the early days before practice appeared to be complete were excluded. The number of responses is quite different for the different cells of the table and these values are given also.

## Table IV

### Means, Standard Deviations, and Number of Responses for the Four Distributions under Controlled Incentive Conditions

| Subject | $t_s$ | $t_\ell$ | $T_s$ | $T_\ell$ |
|---|---|---|---|---|
| | | **Means** | | |
| J.C. | 159 | 201 | 158 | 194 |
| H.G. | 126 | 157 | 124 | 157 |
| J.H. | 142 | 161 | 145 | 154 |
| P.M. | 165 | 192 | 157 | 191 |
| | | **Standard Deviations** | | |
| J.C. | 12.5 | 14.2 | 11.8 | 10.6 |
| H.G. | 27.8 | 16.1 | 18.0 | 18.5 |
| J.H. | 25.8 | 31.0 | 31.6 | 31.3 |
| P.M. | 20.0 | 16.4 | 19.2 | 28.9 |
| | | **Number of Responses** | | |
| J.C. | 133 | 133 | 134 | 144 |
| H.G. | 165 | 173 | 136 | 138 |
| J.H. | 263 | 356 | 67 | 65 |
| P.M. | 179 | 89 | 137 | 138 |

There are no differences which can be attributed to channel uncertainty for any of the four subjects. This is true both for the means and for the standard deviations. For all subjects, the average reaction time to the sound signal is 148 msec. when certain of channel and 146 when uncertain; for the visual signal the values are 178 and 174. The mean standard deviations are 21.5 versus 20.2 for sound and 19.4 versus 22.3 for light.

False-alarm rates are nearly the same for certainty as for uncertainty and there is no reason to believe that the subjects were adopting a lower criterion under uncertainty. The over-all probability of a false alarm was 0.096 when certain of channel and 0.088 when uncertain. The false-alarm rates for the individual subjects are given in Table V.

Table V

False Alarm Probabilities during Certainty and Uncertainty Sessions

| | H.G. | J.H. | P.M. | J.C. |
|---|---|---|---|---|
| certainty | .13 | .11 | .03. | .00 |
| uncertainty | .16 | .06 | .04 | .01 |

## Interpretation

The first three experiments clearly demonstrate that uncertainty as to the sensory channel of the signal has no effect upon detection reaction time. This conclusion holds for each of four subjects. Differential effects of practice are not masking an influence of uncertainty and there is evidence which indicates that differences in criterion level are not acting as a mask either.

All of the experiments used only two channels, one auditory and one visual. The experimental condition of certainty consisted of knowing exactly the channel over which the next signal would arrive while uncertainty consisted of the knowledge that the relevant channel would be one of the two, but not which one. This represents only a minimal manipulation of the degree of uncertainty, and the conclusion must be qualified in this respect. However, all of the obtained differences are very small. If switching of attention is required under the uncertainty condition, the time which is needed to switch between these channels could be, at most, a millisecond or two. The conclusion that the attention switching mechanism is entirely by-passed in this situation is warranted.

In the discussion of the second assumption of the general theory it was pointed out that some sensory messages can be processed without passing over the information channel which is presumed to be controlled by the gating action of attention. The information transmitted in detection reaction time seems to be a member of that class of messages.

This conclusion is based upon data which were obtained after extensive practice with the signals and the task. Very probably, it does not apply when the task is still novel. That skill performance becomes automatic with extensive practice, that it becomes "not-conscious," perhaps because it by-passes attention--these are very old and frequently-heard interpretations of many kinds of performance.

Channel uncertainty, therefore, may influence detection reaction time early in practice, but even if it does, it seems highly improbable that its effect can be measured with the precision required to estimate the theoretical parameters of interest in this study. Reaction times are so highly variable that hundreds of responses are required to attain that goal. Obviously, the parameters will not remain stable long enough.

Therefore, the next step in this series of experiments involved redesigning the reaction time procedure in an attempt to find a procedure in which attention cannot be by-passed, but which still meets the requirements for simplicity which are imposed by the theory.

# EXPERIMENT 4

## DISCRIMINATION REACTION TIME WITH FOUR SIGNALS

The conjecture that channel uncertainty does influence detection reaction time for unpracticed subjects is not entirely baseless. In earlier experiments, which have not been published, it was found to be true. In those experiments only a few responses were measured under each condition for each of a fairly large group of subjects and, when the comparisons are made on a group basis, the effect can be detected. A similar experiment by Mowrer et al (1940) also demonstrates it.

But channel uncertainty has no effect after practice. Thus, it seems that practice changes the mechanisms of information transmission in a basic way.

One hypothesis is that a signal produces excitation at multiple loci in the brain and that a different locus is effective in triggering the response after practice than before. It may be that before practice "cortical excitation" provides the cue to respond, while after practice the relevant excitation is "subcortical," to borrow two very old and very vague concepts from the psychology of motor skills learning.

There is, however, recent neurophysiological evidence which makes such a notion plausible, at least in the present context. It is now quite well established that a stimulus produces two grossly different effects within the central nervous system. Not only does it produce a pattern of excitation within a specific sensory projection area, but it also causes excitation of a most generalized kind in the reticular activating system. Furthermore, every sense modality feeds into the reticular activating system and that system seems to respond to inputs in an undifferentiated, gross manner.

One consequence of these considerations is that we must entertain the probability that the total excitation produced by a visual signal is not entirely isolated from that produced by auditory stimulation. If the two signals in our experiments both excite the recticular activating system as well as each causing excitation in its own appropriate projection area, then the two channels are not entirely independent.

Accordingly, it is hypothesized that visual and auditory signals produce common excitation as well as unique excitation. In addition to the independent sensory pathways there is a common pathway, via the R.A.S., over which <u>at least some</u>, but perhaps very little, information from the eye and the ear can be transmitted. With increasing practice, the probability that the subject will utilize a cue present in the common pathway increases. When, after practice, that cue is used exclusively, channel uncertainty would be without effect. The subject would simply attend to the activation cue under both certainty and uncertainty conditions and there would be no need to switch attention.

We will assume further that the response of the R.A.S. is sufficiently diffuse so that it can transmit detection signals <u>only</u>. On the basis of activation alone, the subject can respond to the occurrence of a signal. But on that basis alone, he cannot discriminate one signal from another.

In the first three experiments the subjects responded to either signal with the same response and withheld response when no signal occurred. Thus, they could have learned to respond to the diffuse excitation which the visual and auditory signals produce in common.

In this experiment, the reaction time procedure was changed to make it impossible to respond to a simple change in activation. Four signals were used, two visual and two auditory, and the subject was required to respond to one visual signal and one auditory signal, but to withhold his response when either of the other two signals occurred. There was, therefore, a change in activation excitation on every trial, but it could not be used as the cue to respond.

In this way, the subject is required to respond to specifically sensory excitation.

## Procedure

The same apparatus was used as in the earlier experiments, except that one visual and one auditory signal were added. A second neon lamp was mounted three inches to the subject's left of the first lamp. A second oscillator, producing a 650-cycle tone over the same headphones, was added.

On every trial under all conditions all four stimuli were presented simultaneously at the beginning of the foreperiod. They remained on for approximately two seconds, at which time one, and only one, of the four terminated. The subject was instructed to respond by releasing the key, which he had depressed to initiate the trial, if either the 2000-cycle tone or the right light terminated. If either the low tone or the left light terminated, he was to withhold the response.

The positive signals were identical to those used in Experiments 1-3.

One-quarter of all trials, 20 trials each day, were catch trials. On ten of these the low tone was presented and on ten the left light was the signal. Fifteen trials of each of the four experimental conditions completed the 80 trials of a day's session. The eight kinds of trial and the number of each which made up one session are summarized in Table VI. "Certain" means that the subject knew in which modality the next signal would occur, but not which of the two possible signals it would be. "Uncertain" means that the subject knew only that any one of the four signals might occur.

Table VI

Number of Trials per Session of Each Experimental Condition in Experiment 4

| Signal | Certain | Uncertain |
|---|---|---|
| High tone | 15 | 15 |
| Right light | 15 | 15 |
| Low tone | 5 | 5 |
| Left light | 5 | 5 |

The same signal response as before was used and no special attempt was made to control incentive.

The 80 trials of a session were presented in a different random order each day. There was a two-minute break after trials 20 and 60 and a twenty-minute break after trial 40.

Prior to each trial, knowledge of modality was provided by means of the auditory ready signal which also instructed the subject to commence the trial. One burst of the ready signal meant that the signal might occur in either modality, two bursts meant that the signal would be visual and three indicated that it would be auditory.

Sixteen male subjects, ranging in age from 17 to 20, were used. Each was run individually with data being obtained on a group of four before a new group of four was started. The first group consisted of the same young men who participated in Experiment 3.

Each group was run until no further practice changes could be detected in (a) means, (b) variances, or (c) false-alarm rates for any of the four. Then additional sessions were conducted until more than 100 responses had been obtained under each condtion for the subject who required the greatest amount of practice. For each subject the data used for the final analysis consisted of all that was recorded after his practice curves had been judged to be asymptotic. The total number of usable responses per subject ranged from 420 to 720.

## Results

Discrimination and detection reaction times, as we have defined them, are very different despite the many important ways in which they are identical. They both employ the same, single response. The signals which cue that response are the same for both. And the amount of information, in the formal sense, which the subject transmits is the same. The difference is in the nature of the signal which cues the withholding of the response. In the detection case, the latter is no signal at all, while in the discrimination case it is a positive signal similar to, but clearly discriminable from those which demand that the response be made.

Even after fairly extensive practice on both, the large differences between the two tasks are clearly evident. A comparison of the two tasks is presented in Table VII for the four subjects who took part in both. The data in the Table are for the channel certainty condition for each signal. For both signals, the mean reaction time is longer, and the extent of variability is much greater for the discrimination task. The percentage increase in variance is much greater than that in means. Further, the difference is substantially greater for the auditory signal than it is for the visual signal. In fact, the difference between the means for the two signals is reversed in direction: for detection, auditory is 30 msecs. faster than visual, as it usually is in reaction time experiments; while for discrimination, visual is 48 msecs. faster than auditory. Apparently, the decision that the lower of the two tones has terminated requires more time than does the decision that the right member of the pair of lights has terminated.

Table VII

Comparison of Detection and Discrimination Reaction Times. Channel Certainty Condition. Averages for Four Subjects.

| Signal | Detection | | Discrimination | |
|---|---|---|---|---|
| | mean | variance | mean | variance |
| Sound | 148 | 499 | 279 | 2538 |
| Light | 178 | 422 | 231 | 1013 |

The effects of practice are large and many trials are required to absorb them. For the twelve subjects who entered this experiment with no previous practice, the mean number of training trials was about 770. One of the 12 required only 320; the other eleven all demanded more than 640, with a maximum of 1200 in one case.

A summary of the data collected during the post-training sessions is presented in Table A-1.of the Appendix for each of the 16 subjects. The following conclusions are immediately apparent:

1. Visual discrimination reaction times are faster than auditory when the subject is certain of the channel of the next signal (16 of 16 cases) and less variable (14 of 16 cases).
2. The net effect of uncertainty as to the channel of the signal is to increase mean reaction time. This occurred for every subject. (Critical ratio = 7.4).
3. Uncertainty as to channel also has the net effect of increasing the variance of the reaction time distributions. This also occurred for every subject.

Therefore, for reaction times which require discrimination, channel uncertainty is important--even with highly-practiced subjects.

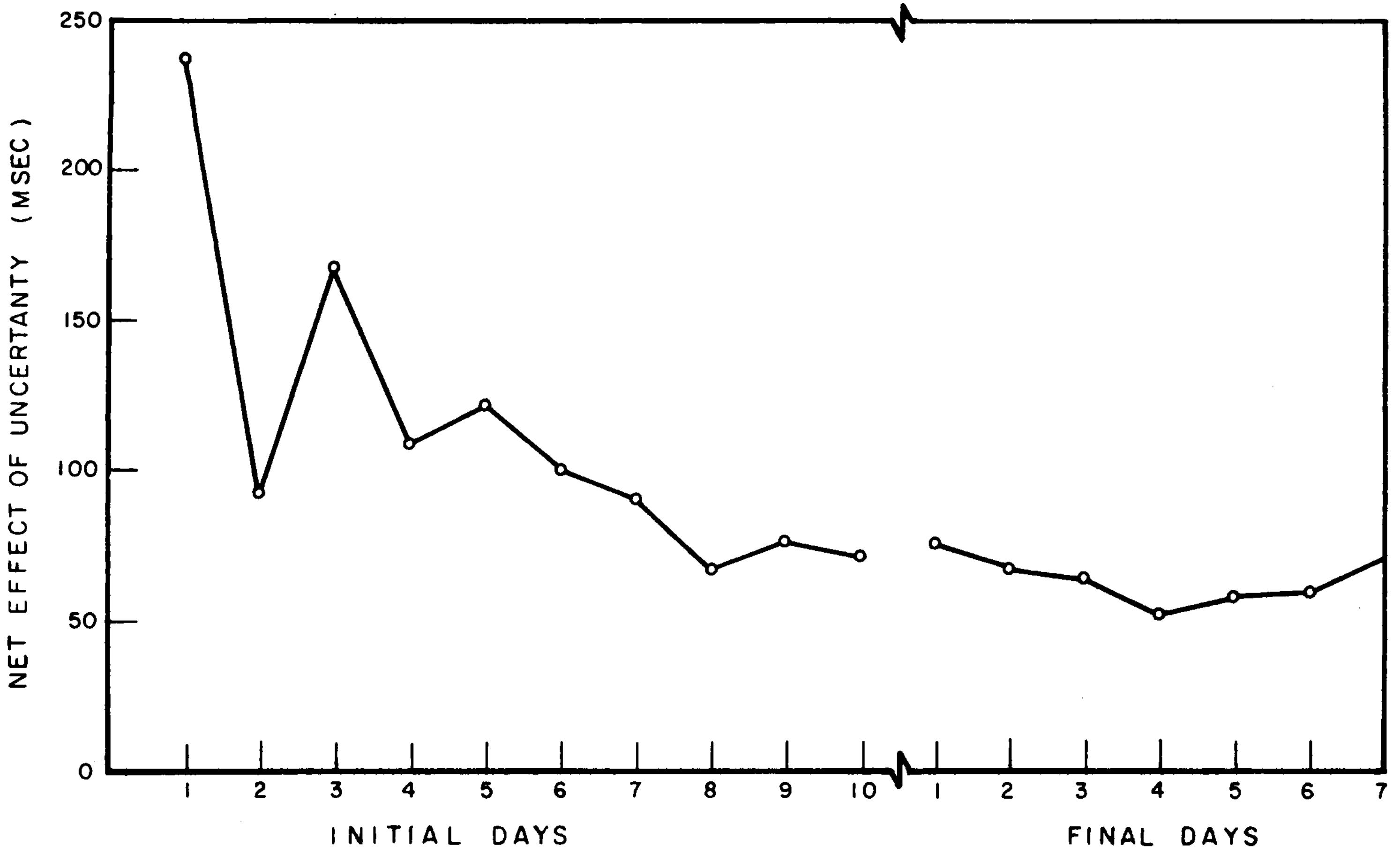

FIG. 6 CHANGE IN NET EFFECT OF UNCERTAINTY DURING PRACTICE. LEFT CURVE SHOWS THE MEAN VALUES FOR 16 SUBJECTS FOR EACH OF THE FIRST TEN DAYS. RIGHT CURVE SHOWS THE FIRST SEVEN OF THE FINAL DAYS.

Further, the influence of uncertainty diminishes with practice, but it appears to level off at a value substantially above zero. This effect is shown in Figure 6 in which the ordinate is the mean value, over subjects, of

$$\Delta = (\overline{T}_{\ell} + \overline{T}_{s}) - (\overline{t}_{\ell} + \overline{t}_{s}).$$

The effect of uncertainty decreases markedly during the first few days of practice, as shown in the left curve of Figure 6, which describes the effect during the first ten days of the experiment. After seven days of practice, there is no indication of a further diminution. The right-hand curve shows the same relationship during the final, or post-practice, period. For this curve, day 1 means the first day after the completion of practice for each individual subject.

There is no evidence of a further change in $\Delta$ during the final sessions. A trend analysis of variance indicates that the hypothesis of zero slope cannot be rejected. (F=1.187,d.f.=6,90).

Every subject emitted some false alarms. The number of false alarms for each of the four conditions is given in Table A-2 of the Appendix for the individual subjects. The over-all false-alarm probability was 0.11 and the range, over subjects, was 0.04 to 0.24. Nearly three times as many false-alarms were given to the auditory signal as to the visual signal, indicating again the greater difficulty of the auditory discrimination.

Table VIII shows the false-alarm rates summarized for all subjects. The probability of a false alarm is somewhat higher when the subject is uncertain as to channel; comparing the total number of false alarms under uncertainty to that under certainty yields, for the group as a whole, a statistically significant difference (t=2.3).

Table VIII

False-Alarm Probabilitities for All Subjects

| | | Signal | |
|---|---|---|---|
| | | Visual | Auditory |
| CONDITION | CERTAIN | .04 | .15 |
| | UNCERTAIN | .08 | .18 |

Now to consider the quantitative effects of channel uncertainty, the data for the individual subjects will be discussed in terms of the scanning model. The parameters of the model can be calculated in two ways, using the means of the four distributions and equations (19) and (20) and the variances with equations (24) and (25). Since $P_s$ is the complement of $P_\ell$ in this model, only $P_s$, the probability that the subject attends the sound channel on a given trial, and M, the period of the attention switching mechanism, need be presented, as they are in Table IX.

All of the values of M are positive, indicating that the net effect of uncertainty is to increase both means and variances. However, the values of M are highly variable and there is little agreement between the two methods of calculation. The mean value of M for all subjects is 125, calculated from means, and 154, calculated from variances. The fiducial limits (at the .05 level of confidence) are 93-157 for means and 136-172 for variances, indicating that the variability is quite large in both cases, but somewhat less for the variance calculations. The difference between the two estimates is not statistically significant (t=1.7) as would be expected considering the wide range of values.

The over-all mean value of M is 139 msecs. Within the meaning of the scanning model, this implies that the average time required to switch attention between channels is approximately 69 msecs.

# TABLE IX

Parameters of the Scanning Model as Estimated from Means and from Variances of Four Signal Distribution Reaction Times

| Subject | Estimate Using Means | | Estimate Using Variances | |
|---|---|---|---|---|
| | $P_s$ | $M$ | $P_s$ | $M$ |
| PM | .71 | 118 | .26 | 137 |
| JC | 1.00 | 36 | 1.00 | 116 |
| JH | .78 | 232 | .06 | 170 |
| HG | .56 | 50 | .03 | 145 |
| RH | 1.00 | 26 | .00 | 145 |
| GH | .29 | 170 | .17 | 192 |
| GS | .20 | 50 | .00 | 130 |
| SB | .35 | 102 | .05 | 204 |
| JM | .23 | 142 | .91 | 129 |
| RB | .27 | 126 | .01 | 151 |
| LW | .94 | 128 | .59 | 155 |
| DH | .78 | 232 | .16 | 112 |
| RBr | .82 | 110 | .00 | 177 |
| DP | 1.00 | 80 | .18 | 127 |
| TM | .82 | 192 | .66 | 128 |
| GK | .55 | 204 | .44 | 240 |

It does not require a much more detailed analysis of these data to convince one that there is little profit in considering each individual subject separately. For at least ten of the sixteen, the difference between the two values of M is very large. And for at least eleven of them the two values of $P_s$ are grossly different. This latter difference reaches the extreme for subject R. H. for whom all of the effect of channel uncertainty upon means is to be found in the visual channel while all of the effect upon variances is to be found in the auditory channel.

Furthermore, there is no correlation, over individuals, between the two values of M (rho=.18).

It was pointed out above that significantly more false alarms were observed under the uncertainty condition. This might be interpreted to mean that the subjects, as a group, assumed a lower criterion under uncertainty and that, as a result, the observed differences in reaction time between uncertainty and certainty are smaller than they would be if the average criterion were the same. To the extent that this is true, the average switching time inferred from these data would be spuriously small. It is also possible that this criterion difference is significantly different among individuals. If so, subjects giving a large ratio of false alarms under uncertainty to those under certainty would be expected to have proportionately lower values of M. This hypothesis was tested by calculating the uncertainty/certainty false-alarm ratio for each subject and correlating it with M. The result (rho=.12) indicates no influence of this factor and this difference among individuals cannot account for the individual differences in M.

These data are inadequate for the purpose of estimating parameters for single subjects and in large part this is attributable to the unexpectedly great within-individual variability which exists for this task. Excluding subjects R. Br. and J. M., for reasons which will be discussed in the next section, and averaging means and variances for the remaining 14 provides the summary statistics contained in Table X. Based on these data, and assuming independence among conditions, the standard error of the parameter M would be expected to be approximately 17 msecs., for samples of 140 responses for each condition. This means that 95 percent of such subjects would be expected to fall within the very wide limits of 57-193 msecs. Actually, 11 of the 16 subjects (70 percent) fall between 50 and 192. Since the expected limits (57-193) assume no between-individual variation, it must be concluded that most of the variation in the individual values of M can be attributed to within-individual variation.

Table X

Four Signal Discrimination Reaction Time.
Average Statistics for 14 Subjects (msec.)

| | Condition | | | |
|---|---|---|---|---|
| | Certainty | | Uncertainty | |
| | Sound | Light | Sound | Light |
| Mean | 289 | 250 | 309 | 292 |
| Variance | 2388 | 1183 | 4678 | 2119 |

For this task to be used to estimate parameters for single individuals, many more hundreds of responses per condition would be required. For example, if N=500 per condition per subject, the standard error of M would be reduced to about 9.2 msecs. and the range of obtained parameters would be approximately 107 to 143.

Finally, let us consider the group data in Table XI in terms of the theoretical models. The value of $\Delta$ is 62 msecs., when calculated from the four means. This mean switching time corresponds to a scanning period of 124 msecs. if the rectangular δ-distribution is assumed. $P_\ell$ and $P_s$ are found to be 0.32 and 0.68, respectively. These parameters can be used to predict the increase in variance which should result from uncertainty. In Table XI this is done for each of the two models.

Table XI

Predicted and Obtained Standard Deviations, Four Signal Discrimination Reaction Time. Group Data

| | Obtained | | Predicted (Uncertainty) | |
|---|---|---|---|---|
| Signal | Certainty | Uncertainty | Scanning Model | Fixed Δ Model |
| sound | 48.9 | 68.4 | 60.3 | 56.8 |
| light | 34.4 | 46.0 | 53.7 | 44.9 |

The average increase in standard deviation which is due to uncertainty is 15.6 msecs., as measured in this experiment. From the distribution means, the scanning model predicts an average increase in standard deviation of 15.4. The fixed-switching time model, on the other hand, predicts an increase of only 9.2.

While the scanning model performs very well indeed in predicting the total increase in variability for the entire group of subjects, any more detailed analysis reveals departures from the model. For example, if the variability increases are considered for each channel separately, it can be seen that the obtained increase is much larger in the auditory channel than in the visual channel while the scanning model predicts a somewhat larger increase for the visual channel.

## Interpretation

Knowing in advance the modality of the next signal is important when a reaction time response is contingent upon a discrimination between signals. In the two-channel four-signal discrimination reaction time task, uncertainty as to whether the next signal will be visual or auditory increases both the means and the variances of the reaction time distributions over the values which are obtained when the modality of the next signal is known exactly.

This effect of channel uncertainty persists after extensive practice and after an initial decrease does not diminish with further practice.

If the temporal effects of channel uncertainty are interpreted as resulting from the added requirement to switch attention between channels on some trials, then the average switching time can be calculated. For the group of subjects in this experiment, the mean switching time is 62 msecs.

A model of the switching mechanism which assumes that the switching time is a constant, fixed value cannot account for the data. Switching times are variable.

A model which assumes that the switching of attention is governed by a periodic mechanism, viz. that the distribution of switching times is rectangular, does agree with the data, but only in a gross way. The period of such a mechanism would be twice the mean, or 124 msecs.

Due in part, at least, to the excessive variability of the measurements of reaction time, the Four-Signal Discrimination Reaction Time task is judged to be inadequate. A major goal of this project is to develop methods of measurement which will yield stable parameter estimates for individual subjects, and it is reasonably clear that the four-signal task will not perform this service.

The excessive variability, in turn, may be due to a flaw in the design of the task. It is by no means certain that the four signals occupy only two channels as required by the theory. The two auditory signals may well be independent of each other and the same might be true of the visual signals. If four, or even three, rather than two channels exist for these signals, then performance would depend upon the particular strategy used in scanning the channels. If a subject chose to scan only one or the other of the two channels which contain the positive signals (i.e. the signals to respond), then it would be the same as a two-channel case. However, a subject might choose to scan one or both channels which contain negative signals in addition. This would add additional variable delays to his reaction time.

It seems very possible that three channels were involved in this experiment, two auditory and one visual. While there is no conclusive evidence for this conjecture, it is supported by the observed greater means and variances for the auditory channel, by our knowledge of critical frequency bands in audition, and by subjective impression.

Additional experiments, similar to this one, but with different numbers and combinations of signals, can clarify this further.

If more than two channels were involved in this experiment, then the parameter estimates based upon the group data would be inflated. Until more is known of channel boundaries, the parameter values given above should be interpreted only with appropriate qualification.

# EXPERIMENT 5

## SUCCESSIVENESS DISCRIMINATION

The time required to switch attention from one independent channel to another should set a lower bound on the time separation between two independent signals which is sufficient to discriminate them as successive rather than simultaneous. Under certain ideal experimental conditions, which have been discussed above in the theory section, the scanning model allows one to deduce a linear relation between the probability of discriminating a successive from a simultaneous pair of signals and the time separation between two signals which make up the successive pair. This probability, P(C), should indicate no better than chance performance, 0.50 in a two-choice method, when the time separation is equal to x, the separation at which the two signals arrive simultaneously in the display areas. As the separation increases above x, P(C) should increase linearly, reaching 1.00 at a separation equal to one period of the switching mechanism (M) greater than x (i.e. at x+M).

This experiment was designed to obtain P(C) versus time functions for this particular theoretical case. The major conditions which must be met in order for the measurement to be useful in estimating the parameters of the model are:

1. The simultaneous pair on each trial, *i.e.*, the standard, must occur in an order opposite to the order of the successive pair, and the members of the simultaneous pair must be separated by an interval which differs from x by an amount less than M.
2. The subject must attend to the channel which contains the signal which occurs first in the successive pair at the moment the first member of every pair occurs.

## Method

Two-choice forced-choice data were obtained for each of the sixteen subjects who had participated in Experiment 4. On each trial two light-sound pairs were presented one after the other, a standard pair and a variable pair. The standard was presented first on half of the trials and second on half.

For every pair, the light and the sound came on together, remained on for two seconds and then terminated. The subject was specifically instructed to try to pick the pair in which the light offset preceded the sound offset (<u>not</u> the "successive pair").

For the standard pair, the stimulus offsets were simultaneous. Since x, the difference in conduction time between the visual and auditory channels, as been shown to be small and positive (auditory faster than visual) in previous work, this zero interval for the standard presented auditory inputs which precede the visual inputs by x msec., a value much less than M.

The light offset preceded the sound, in the variable pair, by one of seven durations, the durations being the 10 msec. steps from 10 through 70 msec. for 12 subjects and somewhat different for the other four subjects.

The subject was required to choose between the first and second pair on each trial. If he chose the variable as the light-first pair, the response is said to be correct and the value of P(C) is the proportion of trials on which this occurred.

One trial was initiated every 15 seconds and two seconds elapsed between the first and the second pairs. This provided ample time for the subject to make his decision and to register his response, which he did by pressing one of two keys. If the response were correct, the subject was so informed.

The same number of trials was presented for each value of the variable and the order of values was random. The subject did not know which value would occur next.

One day's session consisted of 84 trials, divided into two runs of 42. A short break intervened at the halfway point. Performance curves showing only the total percent correct were posted for the subjects' information.

Ample practice was given to all subjects before the final data were collected. The number of practice days varied substantially among subjects, but the final sessions were not begun until changes with practice had ceased. On the first day, every subject was presented with variables ranging from 30 to 90 msec. When a subject's performance had improved sufficiently, usually after two or three days, the difficulty range was shifted to 10-70. Then further practice was given until performance on that range stabilized. It will be seen that this procedure could not be followed for every subject.

All of the sixteen subjects had participated in Experiment 4. All completed that experiment before beginning this one. The stimuli and the physical surroundings of the two experiments were identical.

## Results

Performance improved markedly during practice for every subject but levelled off at an over-all P(C) of approximately 0.80 and remained stable during the final days on which the data were collected which will be discussed in this section. Table XII shows the over-all P(C) for each of the first eleven of the final days.

Table XII

Group Values of P(C) for the Initial Eleven of the Final Days of Data Collection

| Day | P(C) | Day | P(C) |
|---|---|---|---|
| 1 | .79 | 7 | .82 |
| 2 | .78 | 8 | .78 |
| 3 | .80 | 9 | .80 |
| 4 | .78 | 10 | .81 |
| 5 | .78 | 11 | .80 |
| 6 | .82 | | |

The main data, consisting of P(C) for each value of the variable for each subject, are given in Table XIII along with the number of trials upon which each P(C) is based. As can be seen in the table, the 10-70 range of variables was satisfactory for twelve subjects. Two of the remaining four, J. C. and D. H., required only a slight modification of this range. The remaining two, R.Br. and J. M., demanded a radically different range, extending from 40 to 280 msec. in steps of 40. And even this extreme change was not fully adequate for J. M. since he did not exceed a P(C) of .90 even with the 280 msec. variable interval.

These two atypical subjects deserve special comment. It was necessary to begin R.Br. with a range from 240 to 560 msec. After ten days of practice, the range was reduced to 40 to 280. Then eighteen more practice days were needed before his performance stabilized on this range. He was then run for 16 days to obtain the data given in the table. Subject J. M. required thirty days of practice, with several range changes, before he produced his final data. These two subjects are grossly different from the other fourteen, both in the amount of practice they needed and in their final performance.

A straight line was fitted to the data for each subject using a method of least-squares and minimizing the squared deviations in P(C). These lines were fitted to those P(C) values which did not have theoretical magnitudes greater than .975 as predicted from the resulting lines. That is, a line would be determined for all of the data for a subject and if the result yielded theoretical proportions greater than .975 for any points, those points were dropped from the analysis and a new line was calculated for the remaining points.

## Table XIII

## Probability of Correct Response, P(C), for Each Value of the Variable. Standard = 0 msec.

| Subject | N per Point | Value of Variable (msec.) | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | 10 | 20 | 30 | 40 | 50 | 60 | 70 |
| PM | 156 | .532 | .647 | .635 | .737 | .859 | .942 | .987 |
| HG | 168 | .577 | .679 | .774 | .869 | .976 | .958 | .988 |
| JH | 168 | .512 | .679 | .756 | .881 | .976 | .988 | 1.000 |
| GS | 168 | .542 | .643 | .714 | .893 | .952 | .976 | .982 |
| SB | 96 | .542 | .604 | .646 | .719 | .750 | .833 | .854 |
| GH | 180 | .572 | .628 | .661 | .761 | .833 | .922 | .994 |
| RH | 156 | .538 | .603 | .718 | .840 | .904 | .929 | .962 |
| DP | 204 | .598 | .700 | .647 | .706 | .853 | .848 | .882 |
| RB | 168 | .559 | .661 | .792 | .905 | .929 | .994 | .982 |
| TM | 204 | .637 | .662 | .819 | .956 | .975 | .990 | 1.000 |
| GK | 180 | .594 | .678 | .822 | .906 | .961 | .989 | .994 |
| LW | 180 | .583 | .567 | .611 | .761 | .889 | .917 | .939 |
| | | 25 | 40 | 50 | 60 | 70 | 80 | |
| JC | 160 | .619 | .719 | .763 | .850 | .944 | .963 | |
| | | 30 | 40 | 50 | 60 | 70 | 80 | 90 |
| DH | 132 | .538 | .561 | .652 | .773 | .917 | .939 | .955 |
| | | 40 | 80 | 120 | 160 | 200 | 240 | 280 |
| RBr | 192 | .510 | .625 | .734 | .813 | .870 | .938 | .948 |
| JM | 171 | .572 | .628 | .667 | .712 | .812 | .875 | .844 |

Table XIV gives the slopes and y-intercepts of the best-fitting lines. From these, values of x and M were calculated for each subject, x being the value of the interval for which P(C)=0.50 and (M+x) being the value of the interval for P(C)=1.00. The results of these calculations are also contained in Table XIV.

The difference in conduction time between the two sensory channels is generally small and positive. However, in two cases, one being one of the atypical subjects mentioned above, the values of x are negative. And in two cases x is large and positive, one of these being the other atypical individual. Three of the four departures occur for subjects who also give the largest values of M, a fact which might be expected since the large M implies a large variance in switching time, and hence, a large standard error of x. The mean value of x for all subjects is 5.2 msec.

Individuals also differ substantially with respect to the other parameter, the period of attention. Excluding the two atypical subjects, the average value of M is 61.9 msec.; however, it was as small as 42 and as large as 104. The two atypical subjects differ from the mean of the others by factors of four and five (in standard deviation units, 10 and 18).

## Table XIV

### Best-Fitting Lines and Theoretical Parameters Estimated from Them for Each Subject

| S | N | Slope | P(C) Intercept | x | M |
|---|---|---|---|---|---|
| PM | 1092 | .797 | 44.6 | 6.7 | 63 |
| HG | 1176 | .971 | 48.2 | 2.1 | 51 |
| JH | 1176 | 1.010 | 46.9 | 7.5 | 42 |
| JC | 960 | .661 | 45.2 | 7.3 | 77 |
| GS | 1176 | 1.070 | 42.8 | 6.7 | 47 |
| SB | 672 | .535 | 49.3 | 1.3 | 94 |
| GH | 1260 | .704 | 48.3 | 2.4 | 71 |
| RH | 1092 | .754 | 48.3 | 5.0 | 59 |
| JM | 1200 | .130 | 52.2 | -17.0 | 385 |
| RB | 840 | .984 | 47.4 | 2.6 | 51 |
| LW | 1260 | .731 | 46.0 | 5.5 | 68 |
| DH | 660 | 1.021 | 15.6 | 33.7 | 49 |
| RBr | 1080 | .211 | 45.3 | 22.3 | 237 |
| DP | 1428 | .484 | 55.4 | -11.2 | 104 |
| TM | 816 | 1.114 | 49.0 | .9 | 45 |
| GK | 720 | 1.08 | 48.0 | 1.9 | 46 |

The next question concerns the adequacy with which these data are described as linear functions. There are, of course, several ways to answer this and we will consider three of them.

Figure 7 shows the psychophysical data normalized and averaged for the sixteen subjects. The points in this figure are averages obtained by expressing the variable interval scale in units of M. For each subject, each variable interval was calculated as a fraction of the subject's M. The resulting values of all subjects were grouped into ten equal classes from zero to M and the mean calculated for both P(C) and the transformed interval for each of the ten. There is no marked, systematic deviation from linearity.

Psychophysical data are usually described by normal ogives, not by straight lines, and we should question whether ogives give a more adequate description of these data than do the lines which we expect from theory. To attempt to make such a decision, and to check the adequacy of the linear functions in additional ways, further calculations have been made.

Best-fitting ogives, obtained by minimizing squared deviations in gamma and employing Müller-Urban weights, were

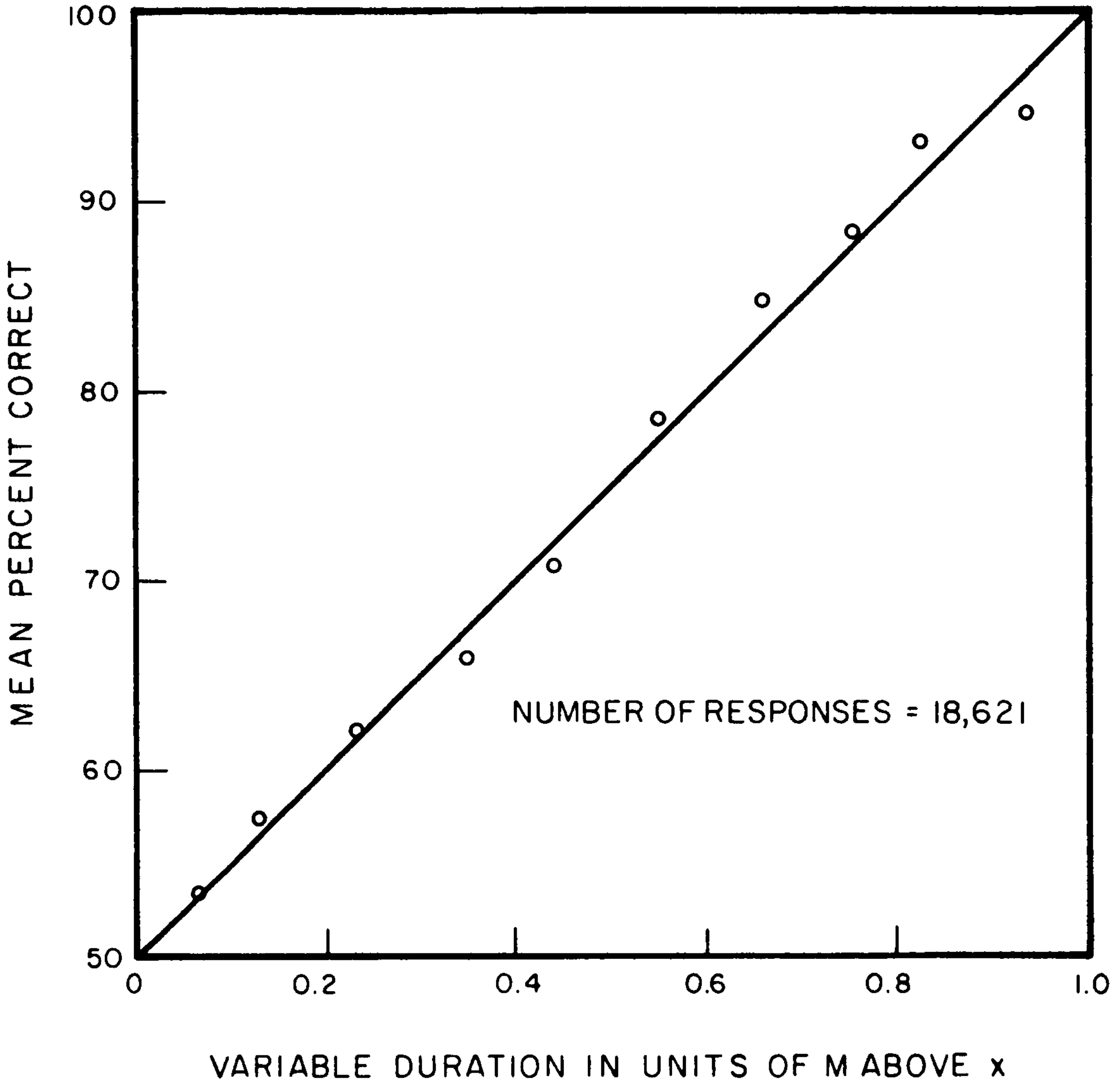

FIG. 7 NORMALIZED DATA FOR SIXTEEN SUBJECTS.

determined for each subject. The data points which were used were the same as those used in the linear analysis, the same values of P(C) near 1.0 being excluded. In performing these calculations P(C) values were corrected for the probability of chance success. The means and standard deviations of the resulting ogives are presented in Table XV.

Table XV

Mean and Standard Deviation

of Best-Fitting Normal Ogive (msec.)

| Subject | Mean | S.D. | Subject | Mean | S.D. |
|---|---|---|---|---|---|
| JC | 45.8 | 23.0 | GS | 31.0 | 14.9 |
| HG | 27.1 | 16.5 | GH | 28.1 | 24.8 |
| JH | 28.9 | 14.6 | RH | 34.3 | 19.8 |
| PM | 38.4 | 20.8 | SB | 48.5 | 32.7 |
| JM | 177.6 | 139.9 | RBr | 139.4 | 80.4 |
| RB | 27.6 | 17.0 | DP | 40.4 | 38.6 |
| LW | 39.5 | 23.0 | TM | 23.1 | 15.7 |
| DH | 58.1 | 16.1 | GK | 25.0 | 16.6 |

One way to evaluate goodness of fit is in terms of the absolute deviation of data points from the fitted functions. In Table XVImean absolute deviations are given for each subject and for each kind of function. The linear and normal fits appear to be equally good. For six subjects the linear fit is the better one while the normal is better for ten. The group averages are almost identical, being .020 for straight lines and .019 for ogives.

## Table XVI

## Mean Absolute Difference between Obtained Proportions and Proportions Predicted by Best-Fitting Linear and Normal Functions

| Subject | Linear | Normal |
|---|---|---|
| PM | .026 | .025 |
| GH | .013 | .012 |
| RH | .023 | .018 |
| SB | .010 | .013 |
| GS | .018 | .017 |
| JH | .016 | .024 |
| HG | .002 | .013 |
| JC | .010 | .018 |
| JM | .021 | .020 |
| RB | .024 | .016 |
| DH | .020 | .011 |
| LW | .042 | .030 |
| RBr | .018 | .020 |
| DP | .031 | .030 |
| TM | .028 | .032 |
| GK | .012 | .008 |
| Mean = | .020 | .019 |

Finally, chi-squared tests of goodness-of-fit were performed with the consequences shown in Table XVII. Four of these thirty-two tests are statistically significant, three at the .05 level and one beyond the .01 level. All of the four are tests of the linear hypothesis. The total chi-squared sums are 86.65 and 62.00 for the linear and normal hypotheses, respectively. The first of these is significant while the second is not. Thus, for the group as a whole it must be concluded that the data depart from linearity in excess of chance expectancy and that they are adequately described by normal ogives. However, this conclusion cannot be extended to single individuals. For at least three-fourths of the subjects, the ogive fit cannot be said to be superior to the linear. In fact, the significance of the linear chi-squared group sum is attributable to one individual, L. W. If his data are excluded, neither group sum is at all close to significance.

### Interpretation

An earlier study of successiveness discrimination (Schmidt and Kristofferson, 1963) supported the hypothesis

## Table XVII

## Chi-Squared Goodness-of-Fit Tests of Linear and Normal Hypotheses

|  | Chi-Squared |  |  |
|---|---|---|---|
| S | Linear | Normal | d.f. |
| JC | 2.426 | 7.253 | 4 |
| HG | 0.101 | 2.510 | 3 |
| JH | 1.023 | 2.412 | 2 |
| PM | 4.569 | 4.151 | 4 |
| GH | 1.825 | 1.321 | 4 |
| RH | 10.472 | 3.496 | 4 |
| RS | 3.565 | 2.256 | 3 |
| SB | 0.566 | 0.801 | 5 |
| RB | 9.702 | 3.275 | 3 |
| JM | 3.695 | 3.305 | 5 |
| DH | 3.206 | 2.373 | 3 |
| LW | 24.829 | 8.888 | 5 |
| DP | 11.073 | 10.422 | 5 |
| TM | 5.093 | 5.924 | 2 |
| GK | 0.753 | 0.351 | 2 |
| RBr | 3.798 | 3.261 | 4 |

that the psychophysical function is linear. The present experiment confirms this finding, but the confirmation is clear for only twelve of sixteen subjects. It must be concluded that the function may be non-linear for some individuals, and that data which are sufficient to define the form of the relationship must be obtained before a linear analysis can be used with confidence to determine the theoretical parameters for a particular individual.

On the other hand, a normal ogive can be used to express the relationship reasonably well for all of the subjects investigated to date.

Any violation of the assumptions of the scanning model will produce non-linearity, according to the model. As one example, it was shown in the section on theory that if a subject fails to switch reliabily from channel to channel at the critical time on every trial, the psychophysical function becomes distorted.

The results of this experiment suggest that some subjects, perhaps one-fifth of the population, cannot maintain the high degree of alertness demanded by the theoretical ideal.

# EXPERIMENT 6

## DISCRIMINATION REACTION TIME WITH THREE SIGNALS

This brief experiment was an attempt to simplify the discrimination task which was used in Experiment 4. As mentioned earlier, it is possible that the four signals which were employed in Experiment 4 occupied three sensory channels rather than two, and the evidence suggests that these were probably two in the auditory modality and one in the visual.

Accordingly, additional data have been obtained for a three-signal discrimination task. The procedure is the same as that of Experiment 4 except that the 650-cycle tone is omitted. The 2000-cycle tone and the right-hand light are the signals which call for the response, the left-hand light signals withholding of the response. In all other respects the procedures are identical to those of the fourth experiment.

Two subjects, J. C. and G. K., who had taken part in the earlier experiments, were continued through this one. Nine days of practice were required by J. C. on this new task and twelve by G. K. The number of post-practice days on which the final data were collected was nine for J. C. and twenty for G. K.

The influence of channel uncertainty was found to be large for both subjects and, as in Experiment 4, there was no indication that the magnitude of the effect of uncertainty diminished with practice.

Obtained statistics describing the raw data are presented in Table XVIII. Comparing these results to the corresponding results for the four-signal task (see Appendix, Table A-1) reveals large and consistent differences between the tasks. All of the means are lower for the three-signal task and, more importantly, the variances are much smaller.

Since both the positive and negative signals are in the visual channel while the auditory channel contains only a positive signal, one might expect a greater effect of uncertainty in the auditory channel since the probability of attending to the visual channel should be higher when the subject is uncertain which channel is relevant. This expectation is fulfilled by the data for both subjects; in both cases the influence of uncertainty upon the reaction time means is much larger in the auditory channel.

## Table XVIII

### Three-Signal Discrimination Reaction Time Results for Two Subjects

| | Auditory | | Visual | |
|---|---|---|---|---|
| | Certain | Uncertain | Certain | Uncertain |
| | | Subject J. C. | | |
| Mean | 186 | 220 | 203 | 205 |
| Variance | 914 | 1722 | 1245 | 1283 |
| Number | 132 | 131 | 134 | 136 |
| | | Subject G. K. | | |
| Mean | 149 | 188 | 154 | 166 |
| Variance | 561 | 742 | 213 | 815 |
| Number | 299 | 299 | 298 | 297 |

If it is assumed that $P_\ell+P_s=1$, then the average attention switching time is not greatly different for the two subjects when the means in Table XVIIIare used for the calculations. These values of $\Delta$ are 36 for J. C. and 51 for G. K.

However, a more detailed analysis reveals that there are striking differences between the subjects. The calculations which are summarized in Table XIX begin to point them out. The obtained variances are repeated in this table so that they may be compared to the variances which are predicted by the scanning and fixed switching time models. These predicted values were calculated using the four distribution means in each case. The two subjects seem to be qualitatively different. For J. C., the scanning model predicts a larger effect of uncertainty upon the variance in the auditory channel than in the visual channel. This agrees with the obtained result. Further, the total magnitude of the increment in variance attributable to uncertainty is accounted for reasonably well by the scanning model. In both of these ways, the fixed switching time model is clearly much less adequate.

The reverse is the case for G. K., although the evidence is not quite as clear. Over-all, the fixed switching time

## Table XIX

### Obtained Variances and Uncertainty Variances Predicted from Parameters Estimated from Means

| | Obtained | | Predicted (Uncertainty) | |
|---|---|---|---|---|
| | Certainty | Uncertainty | Scanning Model | Fixed-Switching Model |
| | | Subject J. C. | | |
| Auditory | 914 | 1722 | 1397 | 992 |
| Visual | 1245 | 1283 | 1351 | 1323 |
| | | Subject G. K. | | |
| Auditory | 561 | 742 | 1724 | 1049 |
| Visual | 313 | 815 | 1014 | 801 |

model is much more adequate for G. K. than is the scanning model. However, the analysis in Table XIX suggests that the fixed switching time model is not entirely satisfactory because the obtained increment in variance due to uncertainty is considerably larger in the visual channel than in the auditory.

Now let us carry the analysis into still greater detail and also compare the parameter estimates with those obtained from the successiveness discrimination measurements. Since the two subjects are very different, they will be discussed separately.

Backing off from the strong assumptions of the two principle models for a moment, it can be shown that J. C. behaves in accord with the assumption that the δ-distribution is rectangular. If it is assumed that the variance of the δ-distribution is zero, the data lead to inconsistent and meaningless inferences such as $P_\ell+P_s=1.3$. If, on the other hand, it is assumed that the δ-distribution is rectangular then $P_\ell+P_s=1.05$. In view of the relatively small number of responses per condition for J. C., this can be accepted as evidence that he did attend to one or the other of the two experimental channels and not elsewhere.

However, $P_s$ is so nearly zero for J. C. that the data for channel $\ell$ do not provide reliable parameter estimates. Therefore, since the assumption that $P_\ell+P_s=1.0$ appears to be satisfactory for this subject, calculations are justified using the scanning model. These indicate that $P_\ell$ is indeed very nearly one; calculating $P_\ell$ from the means gives .94 and from the variances .99, values which agree quite well. The period of the scanning mechanism, M, is somewhat different for the two avenues of calculation: from means it is 72 while from variances it is 97.

In all respects J. C. conforms to the requirements of the scanning model. His successiveness function is linear and it yields a value for M of 84 msec. This number, incidentally, is slightly different from that listed for him in Experiment 5 because it is based upon much more data in addition to that which was obtained in Experiment 5.

Finally, the M of 84 msec. obtained from J. C.'s successiveness discrimination data is the value which best fits his reaction time data for this experiment. The average value of M calculated from the reaction time means and variances is also 84 msec. This means that this single value of M, plus the assumptions of the scanning model, are sufficient to determine the form and the slope of the successiveness function and also the effects of channel uncertainty upon both the means and the variances of discrimination reaction time for subject J. C.

A different picture emerges from the results for G. K. Considering the present reaction time data first, neither the scanning model nor the assumption that the $\delta$-distribution is rectangular can be said to be satisfactory. We have seen the former conclusion earlier and the latter is revealed by calculations for the auditory channel which lead to the inference that $P_s = -.19$.

The assumption that the $\delta$-distribution has zero variance does produce a consistent set of calculations. For one thing, $P_\ell$ is found to be .78 and $P_s$ is .10. Since their sum is .88, the implication is that G. K. failed to attend to either relevant channel on approximately 12 percent of the uncertainty trials. This, in turn, accounts for the partial failure of the fixed switching time model to fit his data, as was brought out above.

The values of $\Delta$ which are inferred upon assuming $\sigma_\delta^2 = 0$ are 54, for the visual channel, and 44 for the auditory. The average switching time is, therefore, 49 msec.

The successiveness discrimination data for G. K. are consistent with the assumptions of the scanning model and yield an estimate of M which is 46 msec., nearly the same as the best single estimate of Δ obtained from his three-signal reaction time data.

By way of summary for subject G. K., it must be concluded that he behaves according to the scanning model in discriminating successive from simultaneous events and shows a basic periodicity of about 46 msec. However, in the discrimination reaction time situation he behaves as if one full period must elapse on every trial on which his attention is not aligned in advance to the channel which contains the signal.

# CONCLUSIONS

The year of work which this report represents has been a fruitful one. The theory of attention has been expanded and numerous, previously unseen implications of it have become evident. Certain empirical relationships have been established with varying degrees of firmness and generality. Many new questions have arisen and the methods needed to answer them have been sharpened. With increased confidence, we can assert that the study of the temporal aspects of attention promises to provide theory of a quantitative nature which will have implications for understanding the processes which control the flow of information within the central nervous system, and that the theory will extend to include important dimensions in addition to the temporal one.

Attention is involved in some tasks and not in others. The same sensory input may or may not need to be processed by attention, depending upon the use which is to be made of its information content. And this influence of the task, in turn, is not rigidly prescribed in all cases; for some tasks it changes as the subject becomes more well practiced.

The first three experiments demonstrated that there is no need to switch attention from one sensory channel to another in order to respond to the mere fact of occurrence of a signal; uncertainty as to the channel which will contain the next signal has no influence upon the time required to respond to the signals, at least after extensive practice. However, even after extensive practice, the time required to discriminate among signals and respond is influenced by channel uncertainty. A delay attributable to the time required to switch attention from channel to channel is interposed when a higher order of information must be processed.

Experiment 4 was the first attempt to measure the switching time of attention using a discrimination reaction time procedure. It was partly successful but not entirely so because extreme variability within individuals precludes its use as a precise method for studying single individuals.

The fifth experiment showed that attention seems to be required when an individual must judge the relative time of events which occur in independent sensory channels. By measuring the probability of discriminating successive pairs of events from simultaneous ones, one can also infer the time required to switch attention between channels.

While Experiment 4 on discrimination reaction time told little about individual subjects, the data may be meaningful when the group of subjects is viewed as a whole. The average time required to switch attention to a new channel was found to be 62 msec. for the four-signal discrimination reaction time method. For the successiveness discrimination measurement of Experiment 5, the average minimum time required between two independent neural events for them to be seen as successive 100 percent of the time was also found to be 62 msec., for the same fourteen experimental subjects.

Experiment 6 involved a redesigning of the discrimination reaction time procedure in an attempt to make it useful for the analysis of single individuals. Data were obtained for only two experimental subjects but they were very encouraging. The variance is much reduced and the influence of channel uncertainty does not disappear with practice. And most importantly, the data for the individual subjects makes sense when analyzed for each one separately. The parameters agree with those obtained with the successiveness measurement. However, the agreement is complex and the two subjects required different interpretations.

One specific hypothesis about the mechanism which controls attention switching was tested in several ways. Briefly, it is the hypothesis that switching is controlled by a periodic mechanism and that switching can occur only once during each period of the mechanism. The group data of Experiment 4 support this hypothesis. It is also supported by the four of the successiveness functions obtained in Experiment 5, but not for every individual subject. Finally, one of the two subjects in Experiment 6 behaves according to the hypothesis in every respect. The second subject utilizes the same time constants, but in a different manner in the reaction time experiments.

Experiment 6 shows that it may be possible to analyze the behavior of single individuals in terms of a quantitative theory of attention. The most pressing need for the immediate future is to increase the number of subjects on which such measurements are available.

The human organism is highly flexible and he is not, usually, limited to a single mode of operation, even in very simple situations. It would be ideal, of course, if a single quantitative mechanism could be defined which would account for the behavior of all people in specified situations. That, of course, is the goal. However, it should not be surprising to find it necessary to conclude that different people operate in qualitatively different ways. Such a conclusion is not yet demanded here, but the evidence is accumulating in that direction. If this is the way people really are, it means only that the theorist who deals in behavior has a more difficult job. It certainly does not mean that scientific theory is ruled out. It does demand that the different mechanisms which are available to different individuals, or even to the same individual, must each be understood. A satisfactory theory will be one which interrelates all of the possible mechanisms successfully, thereby including individual differences within its scope. In the present case, the general theory which is proposed is capable of generating many specific quantitative models, each of which is a possible mode of operation and all of which are tied to the same quantitative theoretical constructs. It is for experiment to decide if and how people differ.

# APPENDIX

## Table A-1

### Experiment 4

Four Signal Discrimination Reaction Time Results
Means, Variances and Number of Responses for Each
of 16 Subjects

| SUBJECT | CONDITION | | | |
|---|---|---|---|---|
| | $t_s$ | $t_\ell$ | $T_s$ | $T_\ell$ |
| | | MEANS | | |
| PM | 306 | 265 | 323 | 307 |
| JC | 277 | 230 | 263 | 262 |
| JH | 272 | 202 | 298 | 292 |
| HG | 261 | 228 | 272 | 242 |
| RH | 322 | 314 | 321 | 328 |
| GH | 306 | 277 | 366 | 302 |
| GS | 275 | 241 | 295 | 246 |
| SB | 329 | 314 | 362 | 332 |
| JM | 344 | 241 | 399 | 257 |
| RB | 248 | 244 | 294 | 261 |
| LW | 309 | 261 | 313 | 321 |
| DH | 317 | 243 | 343 | 333 |
| RBr | 335 | 270 | 345 | 315 |
| DP | 291 | 263 | 278 | 316 |
| TM | 275 | 212 | 292 | 291 |
| GK | 259 | 205 | 305 | 261 |

Table A-1 (continued)

| SUBJECT | CONDITION | | | |
|---|---|---|---|---|
| | $t_s$ | $t_\ell$ | $T_s$ | $T_\ell$ |
| | | VARIANCES | | |
| PM | 2634 | 761 | 4706 | 2062 |
| JC | 3045 | 641 | 2866 | 1766 |
| JH | 1551 | 1684 | 4214 | 2239 |
| HG | 2923 | 968 | 4767 | 1196 |
| RH | 2466 | 2051 | 4215 | 1627 |
| GH | 2563 | 1123 | 6428 | 2983 |
| GS | 736 | 821 | 2138 | 352 |
| SB | 1880 | 1314 | 5681 | 2106 |
| JM | 14364 | 1105 | 14832 | 2657 |
| RB | 2037 | 1636 | 3977 | 1707 |
| LW | 2225 | 1116 | 4510 | 3779 |
| DH | 3400 | 1540 | 4709 | 2129 |
| RBr | 2602 | 1188 | 5227 | 1221 |
| DP | 2354 | 1318 | 4043 | 2248 |
| TM | 2879 | 646 | 4254 | 2441 |
| GK | 2744 | 948 | 8980 | 3026 |
| | | NUMBER OF RESPONSES | | |
| PM | 105 | 105 | 105 | 105 |
| JC | 165 | 164 | 165 | 166 |
| JH | 165 | 165 | 164 | 165 |
| HG | 150 | 150 | 150 | 150 |
| RH | 180 | 180 | 180 | 180 |
| GH | 120 | 120 | 120 | 119 |

Table A-1 (continued)

| SUBJECT | | | CONDITION | |
|---|---|---|---|---|
| | $t_s$ | $t_\ell$ | $T_s$ | $T_\ell$ |
| GS | 120 | 120 | 120 | 120 |
| SB | 120 | 120 | 120 | 120 |
| JM | 165 | 165 | 165 | 165 |
| RB | 165 | 165 | 165 | 165 |
| LW | 165 | 165 | 165 | 165 |
| DH | 165 | 166 | 165 | 164 |
| RBr | 105 | 105 | 105 | 105 |
| DP | 120 | 120 | 120 | 120 |
| TM | 120 | 120 | 120 | 120 |
| GK | 120 | 121 | 120 | 119 |

## Table A-2

### Number of False Alarms for Each Experimental Condition. Four-Signal Discrimination Reaction Time

| | Visual | | Auditory | | | N Per |
|---|---|---|---|---|---|---|
| | Uncertain | Certain | Uncertain | Certain | Total | Condition |
| PM | 3 | 0 | 3 | 2 | 8 | 35 |
| JC | 3 | 5 | 10 | 12 | 30 | 55 |
| JH | 1 | 3 | 6 | 7 | 17 | 55 |
| HG | 7 | 6 | 21 | 13 | 47 | 50 |
| RH | 6 | 0 | 12 | 5 | 23 | 60 |
| GH | 5 | 0 | 2 | 6 | 13 | 40 |
| GS | 1 | 1 | 1 | 3 | 6 | 40 |
| SB | 3 | 0 | 1 | 4 | 8 | 40 |
| JM | 1 | 3 | 19 | 14 | 37 | 55 |
| RB | 6 | 0 | 5 | 2 | 13 | 55 |
| LW | 9 | 1 | 11 | 13 | 34 | 55 |
| DH | 4 | 4 | 6 | 4 | 18 | 55 |
| RBr | 2 | 0 | 8 | 7 | 17 | 35 |
| DP | 4 | 1 | 7 | 8 | 20 | 40 |
| TM | 1 | 1 | 6 | 10 | 18 | 40 |
| GK | 1 | 4 | 15 | 3 | 23 | 40 |

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