Journal of Experimental Psychology:
Human Perception and Performance

VOL. 11, NO. 5 OCTOBER 1985

This document is copyrighted by the American Psychological Association or one of its allied publishers.
This article is intended solely for the personal use of the individual user and is not to be disseminated broadly.

A Psychophysiological Investigation of the Continuous Flow Model of Human Information Processing

Michael G. H. Coles, Gabriele Gratton, Theodore R. Bashore,
Charles W. Eriksen, and Emanuel Donchin
University of Illinois at Urbana-Champaign

Twelve subjects responded to target letters "H" or "S" by squeezing dynamometers with the left or right hand. Targets could be surrounded by compatible (e.g., HH<u>H</u>HH) or incompatible noise (SS<u>H</u>SS) letters. Measures of the P300 component of the event-related brain potential and of correct and incorrect electromyographic and squeeze activity were used to study stimulus evaluation and response-related processes. When incorrect squeeze activity was present, execution of the correct response was prolonged, indicating a process of response competition. This process occurred more often under incompatible noise conditions, which were also associated with a delayed P300. Thus, the noise/compatibility manipulation influenced both stimulus evaluation and response competition processes. In contrast, a warning tone that preceded array presentation on half the trials, increased response speed without influencing evaluation time. The data suggest that the latency and accuracy of overt behavioral responses are a function of (a) a response activation process controlled by an evaluation process that accumulates evidence gradually, (b) a response priming process that is independent of stimulus evaluation, and (c) a response competition process.

When subjects have to respond to visual displays whose elements call for conflicting responses, their reaction times (RTs) are usually prolonged (e.g., the noise/compatibility effect—Eriksen & Schultz, 1979). The present experiment examined this effect by augmenting the traditional tools of mental chronometry with measures of the latency of the P300 component of the event-related brain potential (ERP) and measures of the electromyogram (EMG). These psychophysiological measures are particularly useful in exploring theories, such as the continuous flow model of Eriksen and Schultz (1979), which attempt to account for the noise/compatibility effect. In particular, the measures can provide information about the interactions between processes associated with stimulus evaluation and processes that are required for the actual execution of responses.

Continuous Flow Models of Human Information Processing

A traditional model of the human information processing system can be traced to

---

Some of the data reported in this study were presented at the Joint EEG Society/Psychophysiological Society Meeting, Bristol (England), 1983, and at the 7th Evoked Potentials International Conference, Florence (Italy), 1983.

This study was supported in part by a contract from Air Force Office of Scientific Research, Contract #F49620-83-0144, Al Fregly, Project Director; by Public Health Service Research Career Program Award K6-MH-22014 to C. W. Eriksen; and by United States Public Health Service Research Grant MH-01206.

We wish to thank Rich Carlson, Monica Fabiani, Demetrios Karis, Art Kramer, Mick Rugg, Erik Sirevaag, and three anonymous reviewers for their helpful comments on preliminary versions of the manuscript.

Ted Bashore is now at the Medical College of Pennsylvania at Eastern Pennsylvania Psychiatric Institute, Philadelphia, Pennsylvania.

Requests for reprints should be sent to Michael G. H. Coles, University of Illinois, Psychology Department, 603 East Daniel, Champaign, Illinois 61820.

Copyright 1985 by the American Psychological Association, Inc. 0096-1523/85/$00.75

This document is copyrighted by the American Psychological Association or one of its allied publishers.
This article is intended solely for the personal use of the individual user and is not to be disseminated broadly.

Donders (1969). This model, which has been refined and elaborated by Sternberg (1969), describes a system of elementary processors (i.e., stages) that operate serially. According to this view, a processor is activated upon the *completion* of processing by the preceding element.

An alternative class of models has been proposed in different guises by several investigators (e.g., Eriksen & Schultz, 1979; Grice, Nullmeyer, & Spiker, 1977, 1982; Grossberg, 1982; McClelland, 1979; Turvey, 1973). These models assume that the output of any processor is continuously available to all subsequent, or concurrent, processes. Thus, the partial results of Process A can serve as input to Process B *before* Process A is completed (Eriksen & Schultz, 1979; Grice et al., 1977, 1982; McClelland, 1979).

The continuous flow model of Eriksen and Schultz (1979) is based on the notion that information in the visual modality accumulates gradually over time because of the temporal integrative nature of this sense (Ganz, 1975). According to the model, response activation begins as soon as some visual information is accumulated. Early in the process, the information is consistent with a wide range of responses, and these receive initial activation. As the information continues to accumulate, response activation becomes increasingly focused on responses that remain viable alternatives, given the accumulated data. A given response is actually evoked when the activation of its channel satisfies a criterion. This model assumes, therefore, that during the epoch immediately following the stimulus many responses may be in initial stages of activation. The responses are thus in competition (cf. reciprocal inhibition—Sherrington, 1906). The speed with which a response is executed depends, in part, on the extent of response competition. The greater this competition, the longer the latency of the correct response. A similar model has been proposed by Grice and his colleagues (Grice et al., 1977, 1982).

Consider, for example, the paradigm developed by Eriksen and Eriksen (1974). Subjects are required to move a lever as quickly as possible to the left (right) for the target letter H and to the right (left) for an S. The target letter appears in a clearly defined location, and subjects are instructed to ignore any other letters that occur elsewhere in the visual field. RTs are little affected if the target letter appears flanked by repetitions of itself (compatible noise). However, RTs are appreciably increased if the flanking letters call for the competing response (incompatible noise). Neutral noise letters, that do not call for an experimentally defined response, have an intermediate effect, depending on their feature overlap with the different target letters. If these neutral noise letters share features with the letter that calls for the competing response, they increase RT more than if their features are more congruent with the target letter (Eriksen & Eriksen, 1979; Yeh & Eriksen, 1984).

In accordance with their continuous flow model, Eriksen and his colleagues interpreted the effects of noise/compatibility as evidence that the subject cannot attend solely to the designated target and that both target and noise letters activate their associated responses—that is, they assume a continuous coupling between the processor that analyzes the letter array and the response activation process. The elevated RTs observed when incompatible noise letters appear in the array are due to the activation of both correct and incorrect responses. The responses compete with each other so that the correct response is inhibited and delayed in execution. Furthermore, the effects of feature similarity on RT suggest that the incorrect response can be differentially activated as a function of feature overlap.

On the basis of these studies, Eriksen and his colleagues have argued that the noise/compatibility effect is localized, at least in part, at the response level. To provide further support for this argument, they controlled for the effect of differences in stimulus complexity between compatible and incompatible arrays by assigning each of the two responses to different stimuli (Eriksen & Eriksen, 1979). The subject was instructed to move a lever to the left in response to an H or C and to the right in response to an S or K. In this arrangement, the compatible displays can be as visually complex (e.g., HCH) as the incompatible arrays (e.g., KCK). The data indicated that RT is determined predominantly by the compatibility of the flanking noise and not by the visual heterogeneity of the stimulus array.

Although the continuous flow model appears to provide a satisfactory account of the

This document is copyrighted by the American Psychological Association or one of its allied publishers.
This article is intended solely for the personal use of the individual user and is not to be disseminated broadly.

noise/compatibility effect, the data obtained by Eriksen and his colleagues could also be explained by a strictly serial, discrete stage model, if a number of assumptions are made. Such a model might assume that the stimulus array is "evaluated" in a stimulus evaluation stage and that the results of this evaluation are then passed to a decision stage that identifies the appropriate response. The output of this decision stage is passed to a response execution stage for action. Where would the conflict arise in such a model? Perhaps the conflicting stimuli require a longer evaluation time. Or the full set of information available in the stimulus may be fed to the decision stage so that the choice of response is slowed. It is also possible that a weaker or slower signal is passed to the response execution stage when the preceding stages are subject to conflict.

One of the major differences between continuous flow and serial stage models is the emphasis given to response processes. Serial discrete models (e.g., Sternberg, 1969) typically devote little concern to responses and how they are activated. Their implicit assumption seems to be that on tasks such as choice RT, the end product of the processing stages is a decision or response selection stage whose discrete output is the activation of the appropriate response. As we have seen, continuous flow models (and variable criterion theory, Grice et al., 1977, 1982) do not provide for a separate decision stage responsible for activating or initiating responses. Rather, responses are emitted whenever one of the response channels is activated at a criterion level. This criterion may vary somewhat over trials and conditions, as the subjects adjust their performance to the standards of accuracy expected. Thus, responses can be evoked at different levels of percept development, depending upon the preset criterion, a conception that is consistent with latency operating characteristics or speed–accuracy trade-off functions (Lappin & Disch, 1972a, 1972b).

Another way in which response channels may be activated is through a response priming process that is independent of the nature of the stimulus that is presented and may even precede stimulus presentation. "Aspecific priming" (*aspecific* because the priming is independent of a specific stimulus) may be triggered by such factors as instructions, set, expectancy, pay-off schedules and the like (Eriksen & Schultz, 1979). Note that variations in aspecific priming and variations in response criterion have the *same* influences on response latency and accuracy. Responses that are primed independently of the nature of the stimulus will require less stimulus-related activation for their evocation. Similarly, when subjects lower their criteria for a particular response, less stimulus-related activation is required for an overt response to be given.

As we have seen, the continuous flow model invokes several mechanisms and processes to account for the behavior of overt response systems in the noise/compatibility paradigm. First, there is a process of *stimulus evaluation* that continuously feeds information about the stimulus to associated response activation systems. Second, there is a process of *response competition* by which concurrently activated responses inhibit each other. Third, a process of *aspecific priming* or a mechanism of a *variable response criterion* affects the amount of stimulus-related response activation required for overt response execution. In the next section, we demonstrate how psychophysiological and graded response measures can be used to investigate these processes and mechanisms in the context of the choice RT paradigm used by Eriksen and his colleagues (1974).

Measures

Stimulus-Related Processing

The continuous flow model proposes that responses can be activated throughout the stimulus evaluation process. This view implies that the duration of the evaluation process cannot always be inferred from RT.

One traditional method used to measure the duration of stimulus evaluation has been to derive speed–accuracy trade-off functions (e.g., Pachella, 1974). This method assumes that the accuracy of a response is a function of the evidence accumulated at the time the response is emitted. Thus, by determining the RT associated with a specified level of accuracy, it is possible to infer the duration of stimulus evaluation. However, this method assumes that the duration of stimulus evaluation processes is constant over trials. This assumption may not be valid in all circumstances (e.g., Meyer

This document is copyrighted by the American Psychological Association or one of its allied publishers.
This article is intended solely for the personal use of the individual user and is not to be disseminated broadly.

& Irwin, 1982). Thus, the speed–accuracy trade-off function may not provide an accurate description of stimulus evaluation processes. For this reason, we need a measure of the duration of stimulus evaluation processes *on each trial.* This measure should be unaffected by those processes associated with response selection and execution.

In the present experiment, we use the latency of the P300 component of the ERP as an estimate of the duration of stimulus evaluation. This use of P300 latency was proposed by Donchin (1979) primarily on the basis of two observations. First, he noted that the P300 component is elicited by the rarer of two events that occur in a Bernoulli sequence (see Duncan-Johnson & Donchin, 1977). It turns out that the rule according to which events are categorized can be quite abstract. Because the "rareness" of an event cannot be established until the event has been properly categorized, it is plausible to suggest that the latency of the P300 depends, at least in part, on categorization, or stimulus evaluation, time. The second observation is that, although both P300 latency and RT are sensitive to categorization time, the two measures can be dissociated (Kutas, McCarthy, & Donchin, 1977). As has been noted by many (for example, see Kutas et al., 1977), the latency of P300 may be shorter than, longer than, or equal to the RT associated with an overt response to the same stimulus. Indeed, the correlation between RT and P300 latency is sometimes high and positive, and sometimes close to zero. It is plausible therefore to propose that P300 latency and RT are determined by two, partially overlapping, sets of processes. The degree to which the two measures are correlated will depend on the extent of the overlap between the two sets of processes.

Several studies have confirmed the view that the set of processes that must be completed before P300 is emitted are related to stimulus evaluation but not to response execution. For example, Kutas et al. (1977) required subjects to categorize each of a series of stimuli into one of two classes and to indicate their decision by making a discriminative button-press response. There were three categorization tasks that were given under both speed and accuracy instructions. The first task required subjects to discriminate the name *Nancy* from the name *David;* in the second task, subjects were presented with a list of first names and had to determine which were male names and which were female; in the third task, subjects were presented with a list of words and had to decide whether a given word was a synonym of the word *prod.* Note that the tasks required increasingly complex levels of categorization for their successful execution. Under accuracy conditions, the latency of P300 increased systematically as the level of categorization increased. In the speed condition, P300 latency was shorter for the David/Nancy task than for the other two tasks. The instructions (speed/accuracy) had a large effect on RT (136 ms) but a small effect (19 ms) on P300 latency. The instructions also had an effect on the *correlation* between RT and P300 latency. The correlation was significantly higher when the subjects were instructed to be accurate. It would appear, then, that when subjects try to be accurate, there is more overlap between the sets of processes that determine RT and P300 latency. These data suggest that P300 latency is (a) sensitive to manipulations of stimulus evaluation time (i.e., complexity of the categorization task), and (b) relatively insensitive to manipulations of response-related processes (i.e., speed vs. accuracy instructions).

A more direct test of the proposed relation between P300 latency and stimulus evaluation time was conducted by McCarthy and Donchin (1981). In this experiment, subjects had to execute a choice response as a function of a target word (LEFT or RIGHT) embedded in a 4 × 6 matrix. On half the trials, the rest of the matrix was filled with (#) signs; on the other trials, randomly selected letters of the alphabet completed the matrix. When the background was made up of letters, it was more difficult to detect the target word, and RT correspondingly increased. Another variable that affected RT was response compatibility. On every trial, a warning stimulus (the word SAME or OPPOSITE) preceded the presentation of the matrix. The words occurred in a random sequence and instructed the subjects to respond with the same hand as that indicated in the matrix or with the opposite hand. Thus, the word LEFT could call for a left- or right-hand response depending on the warning stimulus. The type of matrix—(#s) or letters—had a significant effect on both RT and P300 latency, while the response compatibility manipulation significantly affected RT (91 ms) but not P300 latency (16 ms). This result was replicated and

This document is copyrighted by the American Psychological Association or one of its allied publishers.
This article is intended solely for the personal use of the individual user and is not to be disseminated broadly.

extended by Magliero, Bashore, Coles, and Donchin (1984), who found that the effect of matrix type on P300 latency was evident in counting as well as in RT tasks. These authors also found that graded changes in the confusability of the target word and background characters were associated with graded changes in both P300 latency and RT. As in the studies of McCarthy and Donchin, response compatibility had a large effect on RT and a small effect on P300 latency.

It should be noted that the assertion supported by the data reviewed above is that there are processes that have a significant effect on RT but that do not have an effect on P300 latency. In general, these are processes that appear to have a direct relation to the execution of the response. Strong support for this view is provided in a study by Ragot (1984). In this study subjects were instructed to respond with either crossed or uncrossed hands to stimuli that called for a left- or a right-hand response. The cost of hand crossing in RT was substantial (57 ms). However, crossing the hands had no significant effect on P300 latency (2 ms). It would seem, then, that there is strong evidence to support the claim that P300 latency is largely determined by factors that are independent of the "motor" execution of the response.

There remains some controversy regarding the processes that do affect P300 latency. Ragot (1984) noted that it is possible to detect a small effect (19 ms) of "spatial incompatibility" between stimulus and response. This effect is observed with some regularity even though it tends to be small and often not significant. Coles, Gratton, and Donchin (1984) examined this issue and concluded that such effects of spatial incompatibility can be viewed in terms of strategic changes in the evaluation process. For these reasons, it is possible to use P300 latency as an estimate of the duration of the stimulus evaluation process (cf. Brookhuis, Mulder, Mulder, & Gloerich, 1983; Duncan-Johnson & Kopell, 1981; Ford, Roth, Mohs, Hopkins, & Kopell, 1979; Hoffman, Houck, MacMillan, Simons, & Oatman, 1985).[1]

Response-Related Activity

The concepts of response priming and response competition both imply that the activation of the response systems can occur in a graded fashion, without necessarily achieving the level at which an overt response is actually manifested. Thus, to obtain a detailed description of these processes, we need measures of partial response activation that are more sensitive than measures of the overt manifestation of the response. We use EMG measures and "subthreshold" overt responses to provide such a description.

When electrodes are placed over the muscles involved in the overt response, the difference in electrical potential (EMG) can provide information about both the presence and the timing of response activation. Furthermore, although muscle activation must occur if an overt motor response is to be executed, it is possible for muscle activation to occur without a subsequent overt response if either the activation is weak or if the overt response is aborted. Thus, measures of EMG can be used to assess both the presence of partial response activation as well as the time at which response activation has achieved a particular threshold level for the muscles to be activated.

A second method for assessing partial response activation processes involves the use of an analog response device (such as a dynamometer) rather than a discrete manipulandum (such as a response button). If subjects are required to squeeze a dynamometer with a certain force in order to register a response, then measures of the dynamometer's output can be used to assess both the presence and temporal characteristics of an overt response. As with the EMG, such squeeze responses may not achieve the criterion force level for a "response" to be counted, just as a response button may not be pressed to the point of contact

---

[1] Note that we are not asserting that P300 is a manifestation of the stimulus evaluation process itself. Rather we propose that P300 is related to a process that is invoked only after stimulus evaluation has been completed (Donchin, 1981; Karis, Fabiani, & Donchin, 1984). In this regard, we should also note a technical consideration. In the present study, P300 latency is assessed on each trial. Because the P300 occurs in a background of EEG activity, special algorithms are required for its detection. In particular, these procedures involve a search for the *peak* of the P300 rather than its onset. Thus, the onset of the P300 process (and the end of stimulus evaluation) can be assumed to have occurred some time before our measure of the latency of the peak (by at least 100 ms). Thus, P300 latency provides a measure of relative, and not absolute, evaluation time.

This document is copyrighted by the American Psychological Association or one of its allied publishers.
This article is intended solely for the personal use of the individual user and is not to be disseminated broadly.

closure. These partial squeezes may occur if response activation is insufficiently strong or if the response is aborted before complete execution.

These two measures, EMG and dynamometer output, are used in the present experiment to assess the processes of response priming and response competition in the following way. When there is EMG or squeeze activity in a response channel, *but* there is nothing in the stimulus array (target or noise) to call for activation of that response channel, we assume that the process of *aspecific priming* has occurred. If a particular manipulation leads to an increase in the level of aspecific priming of a response channel, less additional activation is required for the threshold for motor response activity to be reached. Therefore, the incidence of EMG and squeeze responses should increase, and they should occur at shorter latencies. *Response competition* is revealed by changes in the temporal aspects of the execution of one response that are associated with the concurrent activation of the other, "competing," response. For example, overt response initiation (as manifested by the EMG) may be delayed, and/or the interval between overt response initiation and completion (as manifested by a squeeze) may be longer, if there is concurrent activation of the other response channel. This concurrent response activation may or may not achieve the thresholds associated with EMG and squeeze activity.

The utility of the EMG measures in the study of response competition is illustrated by the results of a preliminary investigation by Eriksen, Coles, Morris, and O'Hara (in press). These authors measured EMG responses as well as overt motor activity (button presses) in the Eriksen paradigm. Subjects had to respond with the thumbs of the two hands as a function of the target letter. The EMG was recorded from each forearm. Trials were sorted on the basis of the flanking noise (compatible or incompatible) and the presence or absence of EMG activity on the incorrect side. Eriksen et al. (in press) found that incorrect EMG activity occurred more often on incompatible trials and that this incorrect activity tended to appear earlier than the correct EMG activity. Further, on trials when incorrect EMG activity was present, the correct EMG and motor response latencies were delayed. These data provide evidence for a response competition mechanism. The data are also consistent with the continuous flow interpretation of the noise/compatibility effect, because trials on which response competition was evident were more prevalent when the noise was incompatible. However, even when there was no EMG activation on the incorrect side, RTs were still longer for the incompatible arrays. Thus, there was insufficient evidence to attribute all of the noise/compatibility effect on RT to response competition.

Present Experiment

Our psychophysiological exploration of the paradigm described by Eriksen and his colleagues (Eriksen & Schultz, 1979) focuses on the effects of three manipulations. In addition to the noise/compatibility manipulation, we used (a) a manipulation (WARNING) that should affect response-related processes (and EMG and squeeze latency) and (b) a manipulation (BLOCKING) that should affect stimulus evaluation processes (and P300 latency). In this way, we provided different conditions under which RT and P300 latency should be both associated and dissociated.

Noise/Compatibility

We required subjects to make a discriminative response as a function of the central (target) letter in a five-letter array. The flanking noise letters were either the same as the target letter (compatible noise condition) or were those associated with the opposite response (incompatible noise condition). We know from previous research reviewed above that the noise/compatibility manipulation affects RT. In particular, RT is longer in the incompatible noise condition. Eriksen and Schultz (1979) proposed that this effect is due to a greater incidence of response competition. However, this proposal has never been tested directly except in a preliminary study by Eriksen et al. (in press). In the present experiment, we addressed this issue by using measures of partial response activation (EMG and squeeze). We predicted that partial activation of the incorrect response would occur more often in the incompatible noise condition. Furthermore, we looked for direct evidence for the response competition mechanism by evaluating the temporal characteristics of correct response

This document is copyrighted by the American Psychological Association or one of its allied publishers.
This article is intended solely for the personal use of the individual user and is not to be disseminated broadly.

execution when the incorrect response was partially activated. Note that we did not expect that response competition would be absent in the compatible condition. Because incorrect responses can be primed in advance of stimulus presentation, response competition might occur even when the array did not contain information for the incorrect response.

Incompatible noise might also delay processes that occur before response activation. Measures of RT cannot distinguish between this kind of delay and one that is due to response competition. Thus, we obtained measures of the latency of P300 to evaluate the possibility that incompatible noise delays stimulus evaluation. In addition, to understand the elementary processes involved in stimulus evaluation, we examined speed–accuracy trade-off functions. This analysis was designed to study differences in the way information is accumulated in the compatible and incompatible noise conditions.

Warning

On half the trial blocks, a warning tone preceded the presentation of the arrays by 1,000 ms. The tone informed the subject about the timing of array presentation but conveyed no information about the nature of the array. This kind of alerting stimulus should speed RT by facilitating motor preparation rather than stimulus evaluation (cf. Posner, 1978). RT measures cannot easily distinguish between stimulus evaluation effects and motor processes. However, the latency of P300 should be sensitive only to variations in stimulus-related processes. Thus, we predicted that P300 latency would be unaffected by the provision of an alerting stimulus. On the other hand, measures of motor processes (EMG and squeeze) should be affected. In particular, if the level of aspecific priming is higher following the warning, then we would predict that partial response activation should be more evident in warned than in unwarned conditions.

Blocking

Finally, we evaluated the effects of fixing the level of noise within trial blocks. The level of noise was either constant or variable for a series of trials. This manipulation was chosen to study the stimulus evaluation process in detail. In particular, we wanted to create conditions for which complete evaluation was unnecessary for successful task performance (cf. Kutas et al., 1977). By presenting only compatible noise arrays in a trial block, we gave subjects the opportunity to respond correctly without localizing the central target letter, because all the letters in the array were the same. When the noise was always incompatible, the evaluation process could also be facilitated because the central letter was consistently different from the lateral letters. Thus, we predicted that P300 latency (and RT) would be shorter when the level of noise was fixed within a block of trials.

Method

Subjects

Twelve male students at the University of Illinois (between the ages of 18 and 23) served as subjects. They were paid $3.50 per hour, plus a bonus for participating in all sessions.

Design

Subjects were required to make a discriminative response as a function of the target letter in a five-letter stimulus array. They received 12 blocks of 80 trials during each of two sessions. The first 8 blocks of the first session were considered training, and the data obtained from these blocks were not used in the analysis. The remaining 1,280 trials (16 blocks) were divided as follows:

Task. In half (8) of the blocks the subjects were instructed to *respond* with one hand to the target letter H, and with the other to the target letter S. The relation between responding hand and target letter was counterbalanced across subjects. In the other half of the blocks the subjects were instructed to *count* one of the two target letters (counterbalanced over subjects).

Noise. On half the trials, the target letter was surrounded by the same letter (*compatible* noise); on the other half, the surrounding letters were those calling for the opposite response (*incompatible* noise).

Blocking. In half of the blocks, the *fixed* condition, only one type of noise was presented (compatible or incompatible), whereas in the other half, the *random* condition, both types of noise were presented at random. In each case, the probability of each target letter was .5.

Warning. For half the blocks, a warning tone preceded the stimulus. In the other half, no warning was given.

As a result of these manipulations, 80 trials were obtained for each of 16 conditions defined by the factorial combination of two types of task, two types of noise, two types of blocking, and two levels of warning. Note that, with the exception of noise, the level of each variable was always constant for a given block of trials. Trial blocks were randomly ordered with the constraint that no more than two consecutive blocks could have the same level of task, warning, or blocking.

This document is copyrighted by the American Psychological Association or one of its allied publishers.
This article is intended solely for the personal use of the individual user and is not to be disseminated broadly.

Apparatus and Procedure

On each trial, one of four stimulus arrays, HHHHH, SSSSS, SSHSS, and HHSHH, was back-projected on a translucent screen using a Kodak random access slide projector. Stimulus duration (100 ms) was controlled by a shutter. The interval between two consecutive stimulus presentations varied randomly between 4,500 and 6,500 ms. The subject sat facing the screen at a distance of two meters so that the angle subtended by each letter was 0.5°. Thus, the visual angle subtended by the entire array was 2.5°. A fixation point, placed 0.1° above the location of the central target letter, remained visible throughout the experiment.

In the *respond* conditions, the task of the subject was to respond to the central target letter (H or S) by squeezing one of two zero-displacement dynamometers (Daytronic Linear Velocity Force Transducers, Model 152A, with Conditioner Amplifiers, Model 830A; see Kutas & Donchin, 1977). The force applied to the dynamometer was transformed into a voltage by the transducer. This voltage was digitized at 100 Hz for 1,000 ms following array presentation. The output of the transducer was processed by a circuit to determine when the force exceeded a prescribed criterion value. This value defined the occurrence of an overt response and was used to determine RTs. Before the practice trials, the value of each subject's maximum squeeze force was determined for each hand separately. Then, criterion values corresponding to 25% of maximum force were established. During the practice trials, a click was presented to the subject over a loudspeaker whenever the force exerted on the transducer crossed the criterion.

In the *count* condition, subjects were required to count the number of trials on which a designated central target letter was presented. For half the subjects, the counted letter was H, while for the others it was S.

On half the blocks, a warning tone (1000 Hz, 50-ms duration, 65 dB re 20 $\mu N/m^2$) preceded the presentation of the array by 1,000 ms. These blocks constituted the *warned* condition. Note that the interstimulus interval (time between arrays) was the same for both warned and unwarned blocks.

For half the blocks, the level of noise (compatible or incompatible) was *fixed* within a block; for the other half it was *random*. Thus, in the fixed condition only two of

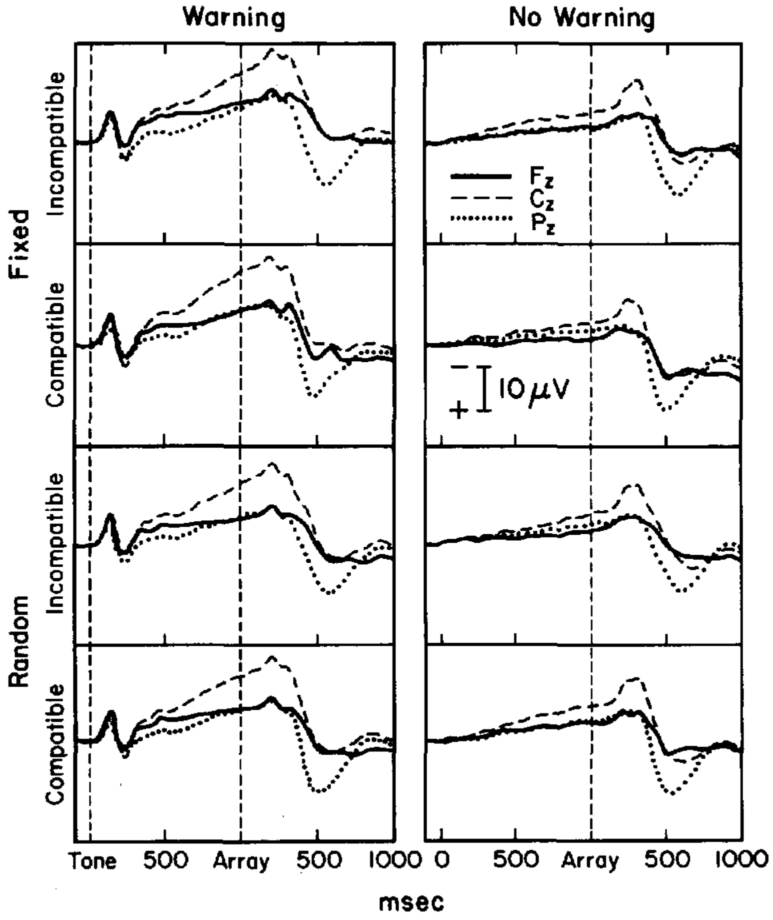

Figure 1. Event-related brain potential (ERP) waveforms (in microvolts averaged over subjects) for three electrode locations: frontal (Fz), central (Cz), and parietal (Pz). (Separate waveforms are shown for the eight different experimental conditions of the respond task.)

This document is copyrighted by the American Psychological Association or one of its allied publishers.
This article is intended solely for the personal use of the individual user and is not to be disseminated broadly.

the four arrays were presented, while in the random condition any one of the four arrays could occur on any trial.

Psychophysiological Recording

The electroencephalogram (EEG) was recorded from Fz, Cz, and Pz (according to the 10/20 international system, Jasper, 1958) referenced to linked mastoids using Burden Ag/AgCl electrodes affixed with collodion. Vertical electrooculographic activity (EOG) was recorded from Burden electrodes placed above and below the right eye. The EMG was recorded by attaching pairs of Beckman Ag/AgCl electrodes on both the right and the left forearm using standard forearm flexor placements (Lippold, 1967). For EEG and EOG electrodes the impedance was less than 5 Kohm; for EMG, impedance was below 15 Kohm.

The EEG and EOG signals were amplified by Grass amplifiers (model 7P122), and filtered on-line using a high-frequency cut-off point at 35 Hz and a time constant equal to 8 s. The EMG signals were conditioned using a Grass Model 7P3B preamplifier and integrator combination. The preamplifier had a ½ amplitude low-frequency cut-off at 0.3 Hz, while the output of the integrator (full-wave rectification) was passed through a filter with time constant of 0.05 s.

In each case, the derived Voltage × Time functions were digitized at 100 Hz, for an epoch of 2,100 ms starting 1,100 ms before array presentation. For the warned condition, this provided a 100-ms sample before the presentation of the warning tone.

Data Reduction

Overt responses. As we noted above, the subjects were required to squeeze the dynamometers to a criterion of at least 25% of maximum force to register a "response." Thus, an overt response was deemed to have occurred if this criterion was achieved, and RT was defined as the interval between array onset and the point at which the criterion was crossed. By evaluating the outputs of both force transducers, we were able to establish both the accuracy and the latency of these overt responses on every trial.

The squeeze response requirement was used to provide additional information about the dynamics of overt response execution. Thus, the output of the force transducer could be used not only to assess when the force exerted by the subject crossed the criterion but also to determine when an overt response was initiated. In particular, we established the minimum value of output of the force transducer that was discriminable from noise. This value became the criterion for overt response *initiation*, and the time at which this occurred was used to define the latency of squeeze *onset*.

In this way, for each squeeze of either dynamometer to criterion, two latency measures were available: the latency of squeeze onset and the RT. Because the outputs of both dynamometers were evaluated on each trial, these two measures were available for both correct and incorrect responses. Furthermore, on some trials overt responses were initiated but not completed—that is, the force exerted did not exceed the 25% criterion. Thus, for these trials we were able to determine both the presence and latency of "partial" squeezes. When they occurred, these partial squeezes were generally made by the incorrect hand and were accompanied by complete overt response execution by the correct hand.

Psychophysiological data. For every trial, the variance of the EOG activity was computed. When this exceeded a preset criterion, the data from that trial were discarded. In fact, this occurred for less than 10% of the trials. To provide a sense of the ERP waveforms recorded under the conditions of the experiment, we show in Figure 1 the grand average ERPs for the eight conditions of the RT experiment. Note that negative going potentials are represented by an *upward* deflection of the curve.

For the warned condition, we note a response to the warning stimulus followed by a slow increase in negativity (particularly at Cz) that may correspond to the contingent negative variation (CNV, Walter, Cooper, Aldridge, McCallum, & Winter, 1964). The stimulus array elicits a "classic" P300 characterized by maximal positivity at the Pz electrode. In the unwarned condition, we also see the classic P300 following presentation. The ERP data for the count conditions will not be considered in detail. These conditions were included to confirm that any effects of the independent variables on ERP measures in the RT task could not be attributed to the motor response requirement.

The single-trial data from the three scalp electrodes (Fz, Cz, and Pz) were smoothed using a low-pass digital filter (high-frequency cut-off point at 3.14 Hz, two iterations). The three waveforms were then combined to yield a composite waveform by differentially weighting the three electrodes (vector filter, Gratton, Coles, & Donchin, 1983). The weights were chosen to reflect the scalp distribution usually observed for P300 (Pz > Cz > Fz). This procedure has proved to be both reliable and valid (Gratton, Kramer, & Coles, 1984; Fabiani, Gratton, Karis, & Donchin, in press). P300 latency was then estimated by finding the latency of the maximum value of the composite waveform in a time window between 300 ms and 1,000 ms after array presentation. In this way, for each individual trial, except those where excessive eye movements occurred, a value for P300 latency was obtained.[2]

For the respond task only, the integrated EMG activity from both arms was evaluated on each trial. The integrated EMG traces typically exhibited small, unsystematic, variation prior to array presentation. Following the array, a response was observed in one or both traces. To determine the latency of the onset of an EMG response and to evaluate whether an EMG response was present, a criterion value was established. This was accomplished using a procedure similar to that described above for the onset of squeeze activity. Thus, we determined (for each subject) the minimum value of the integrated EMG output sufficient to discriminate a change from random variations in background EMG. When the integrated EMG exceeded this criterion, an EMG response was deemed to have been initiated, and the latency of this activity was noted. As with

---

[2] We should note that we also used a more traditional method, peak-picking at Pz, to determine the latency of P300 on single trials. There was a close correspondence between the data obtained using the traditional procedure and those from vector filter. However, analyses of latency measures derived from the vector procedure yielded consistently higher F values than those based on the peak-picking procedure.

This document is copyrighted by the American Psychological Association or one of its allied publishers.
This article is intended solely for the personal use of the individual user and is not to be disseminated broadly.

the squeeze responses, EMG responses in both arms could be observed on the same trial.

Results and Discussion

This section is organized in the following way. First, we present the results of an analysis of the RT and error data. This will show that we have replicated the effects of noise/compatibility reported by Eriksen and his colleagues and that both warning and blocking have effects on these measures. Second, to provide evidence that partial response activation occurs in this paradigm, we present analyses of graded responses. Then, we consider how partial activation is related to measures of the latency of the psychophysiological and squeeze responses. Next, we review the data relating to the effects of the three manipulations—noise, warning, and blocking—on partial activation and stimulus evaluation. Finally, we present speed–accuracy trade-off functions for the different conditions of the experiment as well as for different latencies of the P300 responses.

Reaction Time and Error Rate

The RT data replicated the results reported by Eriksen and Eriksen (1974). Subjects responded faster to compatible noise arrays (397 ms) than to incompatible noise arrays (444 ms). Furthermore, both warning and blocking manipulations affected RT. When a warning tone preceded the presentation of the stimulus array, RTs were shorter (410 ms) than when no warning was given (430 ms). When level of noise was fixed within a block of trials, RTs were shorter (413 ms) than when both compatible and incompatible arrays could occur (428 ms). However, the advantage for the fixed condition was more pronounced for compatible arrays (19 ms) than for incompatible arrays (11 ms).[3] These effects can be seen in Figure 2. They were supported by an analysis of variance (ANOVA) on mean correct RTs for each subject and each of the eight conditions (defined by the three manipulations), which revealed significant main effects of noise, $F(1, 11) = 129.59$, $p < .001$; warning, $F(1, 11) = 44.39$, $p < .001$; and blocking, $F(1, 11) = 15.60$, $p < .01$; and a significant interaction between blocking and noise, $F(1, 11) = 5.14$, $p < .05$. Note that, for this analysis, RT was defined as the latency at which the squeeze response crossed the criterion (25% of maximum force).

Errors (defined as squeezes above the 25% force criterion with the incorrect hand) were analyzed using a similar ANOVA. Mean error rates for the different conditions are shown in Figure 2. Subjects made more errors in response to incompatible noise arrays than on compatible noise trials, $F(1, 11) = 30.97$, $p < .001$. However, the effects of noise and blocking interacted, $F(1, 11) = 34.53$, $p < .001$. In fact, fixing the level of noise for a block of trials reduced the error rate for the incompatible noise condition but increased the error rate for the compatible noise condition.

When these data are considered together with those for RT, the following picture emerges. For compatible noise, error rate is larger and RT shorter for the fixed than for the random condition. This suggests that subjects adopt a less conservative strategy in the fixed condition. In contrast, for incompatible noise, error rate is smaller and RT shorter for the fixed than for the random condition. This pattern of data cannot be readily explained in terms of a difference in the conservatism of the response criterion. Rather, it appears that the processing of the incompatible array is facilitated in fixed versus random conditions. As we shall discuss later, we believe that this processing advantage is actually present for both compatible and incompatible conditions. However, it is not apparent in the compatible condition because of a concurrent change in strategy. The problem of interpretation introduced by variations in response strategy may be resolved by the P300 data, which we consider later.

Graded Response Analysis

One major aim of this experiment is to explore the role of response competition and aspecific priming in the noise/compatibility paradigm. In this section, then, we consider evidence for the presence of partial response activation. Next, we review the results of analyses of the effects of the three experimental manipulations on both the frequency and the

---

[3] When a significant interaction was obtained, an analysis of simple main effects was performed to interpret the interaction. In all cases, the alpha level was set at .05.

This document is copyrighted by the American Psychological Association or one of its allied publishers.
This article is intended solely for the personal use of the individual user and is not to be disseminated broadly.

latency of partial activation of response channels.

The EMG and squeeze measures serve as the basis for identifying four levels of response activation for each of the two response channels (left/right or correct/incorrect hand). These levels are zero activation, EMG activation, partial squeeze activation, and criterion squeeze activation (a squeeze with at least 25% maximum force). In principle, then, we could have identified many different configurations of response activation in our data set. However, the number of configurations is limited for both practical and theoretical reasons. First, the levels of activation within a given channel are not independent. Thus, if a criterion squeeze is evident in a channel, EMG activation and partial squeeze activation *must* have occurred in that channel. This restricts the number of possible configurations to 16. Second, trials on which neither channel achieves a criterion squeeze level are uninteresting because, in traditional terms, no response occurred. Third, some configurations occur so infrequently that reliable estimates of their characteristics are not possible. For example, subjects seldom exhibit criterion squeeze responses in both channels. These considerations led us to consider only four response configurations for the purposes of classifying the

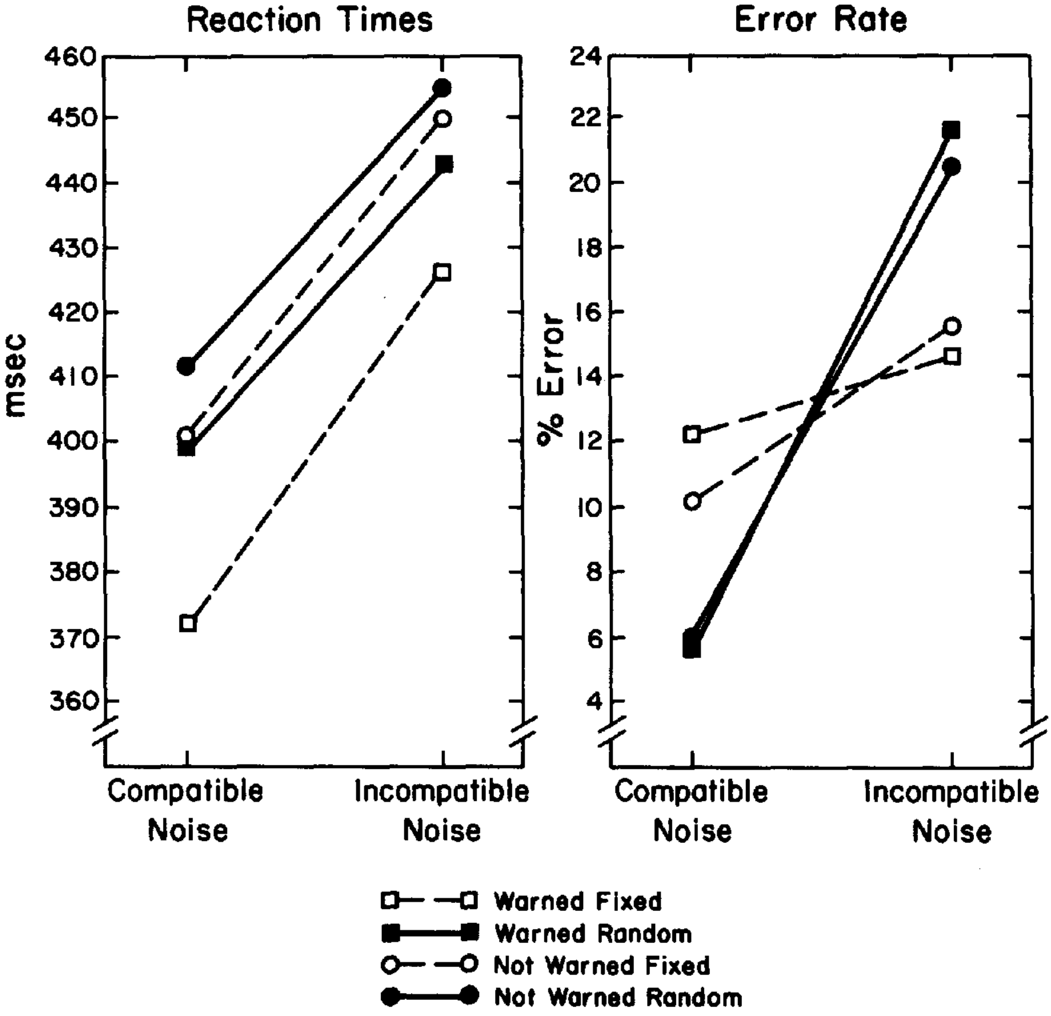

Figure 2. Reaction times (in milliseconds) and error rates as a function of noise, warning, and blocking conditions.

This document is copyrighted by the American Psychological Association or one of its allied publishers.
This article is intended solely for the personal use of the individual user and is not to be disseminated broadly.

trials. These four configurations have the property of including (a) completely correct trials, where there is no evidence of partial activation of the incorrect response channel; (b) correct trials for which there is partial activation of the incorrect response channel at the level of the EMG; (c) trials with squeeze activity on both sides, which, depending on whether or when a criterion squeeze occurs, may be correct or incorrect; and (d) completely incorrect trials, which may or may not include partial EMG activation of the correct channel. In fact, 99.4% of all trials could be classified into one of these four categories.

The formal definitions of the four configurations are as follows:

N	Activity only on the correct side in EMG and squeeze channels. (*N*o activity on the incorrect side)
E	Activity on the correct side for EMG and squeeze channels; activity also present for EMG on the incorrect side. (*E*MG activity on the incorrect side)
S	Activity on the correct side for EMG and squeeze channels; activity also present for both EMG and squeeze channels on the incorrect side. The incorrect squeeze may or may not reach the 25% of maximum force criterion. (*S*queeze activity on the incorrect side)
Error	Activity on the incorrect side for EMG and squeeze channels; EMG activity on the correct side may or may not be present. However, no correct squeeze activity is present.

Note that in terms of a conventional error analysis, trials classified as either N or E would be considered "correct" trials. On the other hand, trials classified as Error would be considered "incorrect" trials. The S trials might be considered either correct or incorrect, depending on the magnitude and timing of the two squeeze responses. However, on most trials, the incorrect response (partial or complete) preceded the correct response (see below).

For each subject and each of the eight conditions, we determined the number of trials falling into each of the four categories described above (N, E, S, and Error) and then expressed the frequency of trials in each category as a percentage of the total number of trials for that condition. The mean percentages over subjects and conditions were N = 47%, E = 31%, S = 16%, Error = 6%. Thus, on 47% of the trials (E and S), partial activation of the incorrect response channel occurred even though the correct response was also activated. Note that half the S trials were counted as incorrect responses in the traditional error analysis described earlier.

In spite of our efforts to assure that each response category was associated with a sufficient number of trials, for 1 subject for some conditions no trials were classified in the N category. This subject's data were not considered in any of the subsequent analyses. For 7 other subjects, the Error category was sometimes empty. The data for these subjects were retained for most of the analyses. The frequencies with which trials were classified in each category as a function of condition are shown Figure 3.

Latency analysis. We now consider the relation between our response classification system and measures of the latencies of EMG and squeeze onset for the correct side, EMG and squeeze onset for the incorrect side, and P300. The effects of the experimental manipulations on these latency measures are also analyzed.

Figure 4 shows mean latency values for the different conditions of the experiment for each of the five latency measures. The data are segregated for the four response categories. To highlight the effects of the noise/compatibility and warning manipulations, we present the latency data for these manipulations in Figures 5 and 6, respectively. The latter two figures also provide information about the frequency of the different response categories for the two manipulations.

a. *Response classification.* The analyses to be reported in this section are designed to address three questions: (a) Does our response classification system represent a "degree of error dimension"? (b) Does response competition occur when two response channels are activated concurrently? (c) Is the degree of error related to the time required to evaluate the stimulus?

Inspection of Figures 4, 5, and 6 suggests that the pattern of latencies varies with response category. These variations are consistent with the view that the response categories

This document is copyrighted by the American Psychological Association or one of its allied publishers.
This article is intended solely for the personal use of the individual user and is not to be disseminated broadly.

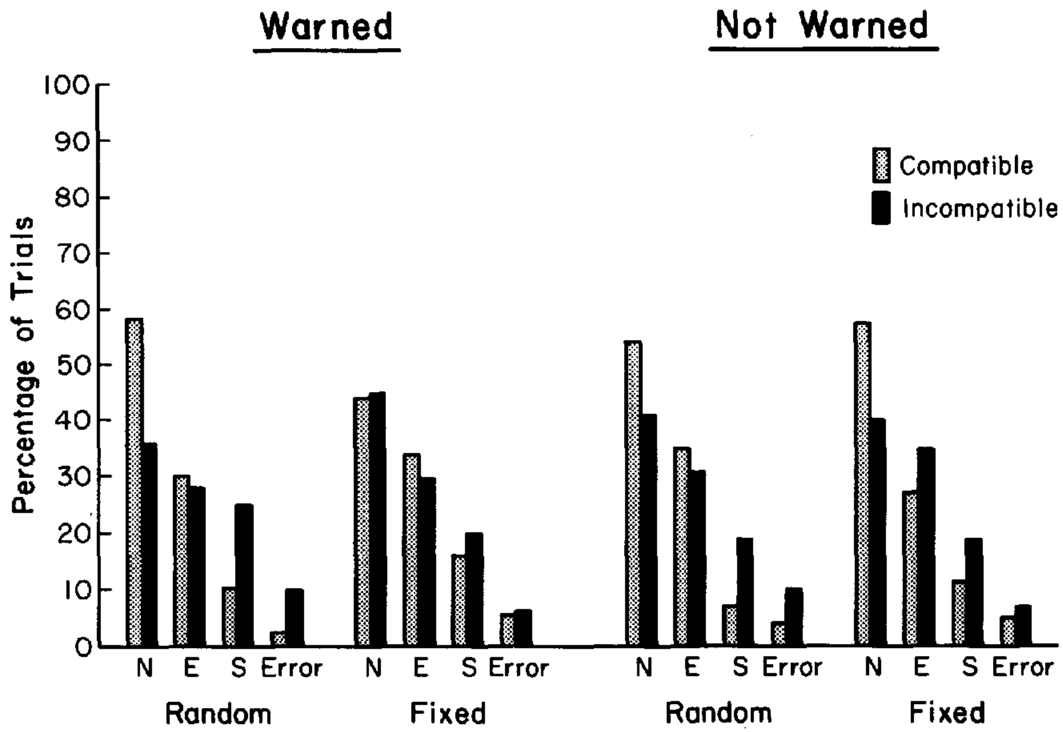

Figure 3. Frequency distributions of trials as a function of the four response categories. (*N, E,* and *S* are correct response trials associated with either no [N], electromyographic [E], or squeeze [S], activity on the incorrect side. *Error* trials are associated with an incorrect squeeze and no correct squeeze activity [see text]. Separate distributions are shown for the eight different experimental conditions.)

can be considered as ordered levels of a degree of error dimension. In fact, the onset latency of correct motor activity (both EMG and squeeze) increases monotonically from the N to E to S categories. Similarly, the latency of the incorrect motor activity decreases monotonically from the E to S to Error categories. These conclusions are confirmed by ANOVAs whose results are reported in Table 1.[4] Thus, for both correct and incorrect response channels, the latencies of EMG and squeeze onset are longer when activity is present on the other side. Furthermore, there is a larger increase when the contralateral activity includes a squeeze than when it includes only EMG activity. Because responses are delayed to the degree that activation of the competing response channel occurs, these data satisfy our criterion for the existence of a response competition mechanism.

Further support for the response competition mechanism comes from an analysis of the interval between the initiation of the correct response (as shown by the onset of EMG activity) and its execution (as shown by the onset of squeeze activity). This interval was longer for the S (80 ms) than for the E (53 ms) and N (57 ms) categories, $F(2, 20) = 32.30$, $p < .001$. These results indicate that as the amount of motor activity on the contralateral side increases (from N and E to S), the execution of the correct response is disrupted.

---

[4] Whenever a significant main effect was obtained for a factor with more than two levels, Tukey's HSD test (Tukey, 1953) was used to determine which levels were significantly different from each other (alpha level = .05). For the latency of correct activity (both EMG and squeeze onset), the S category was longer than N or E, which did not differ significantly from each other. For the onset latency of incorrect EMG activity, the Error category was shorter than the E category. Note that, whenever the Error category was included in an analysis, the ANOVA was based on the data from 4 rather than 11 subjects. However, the picture that emerges from the analysis of 4 subjects replicates that provided by the whole sample of 11 subjects as far as the differences among N, E, and S are concerned.

This document is copyrighted by the American Psychological Association or one of its allied publishers.
This article is intended solely for the personal use of the individual user and is not to be disseminated broadly.

Thus, not only is the onset of a response delayed when there is squeeze activity in the contralateral side but also the actual execution of the response is prolonged. These data confirm the existence of a response competition mechanism.

A further interesting finding comes from a comparison of the latency of the onset of the squeeze response on the correct and incorrect sides. This comparison can be performed only when squeeze activity is present on both sides—that is, for the S category. In this case,

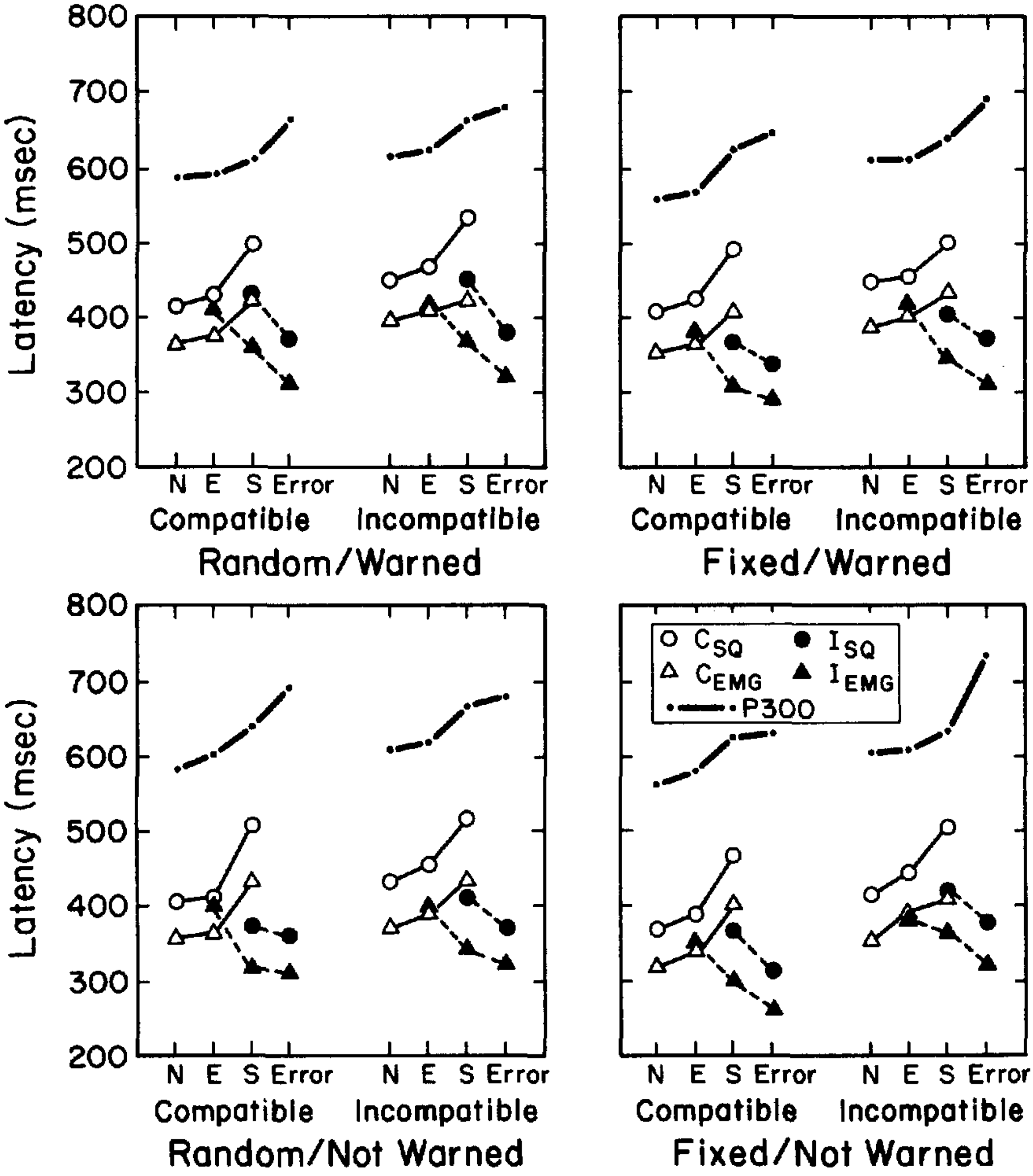

Figure 4. Values (in milliseconds) for the five latency measures as a function of response category and the eight conditions of the experiment. (For N, E, and S categories, the latency data are based on 11 subjects. For the Error category, the data are based on 4 subjects [see text]. P300 = latency of the P300; Csq = latency of onset of the correct squeeze response; Cemg = latency of onset of the correct electromyogram [EMG] response; Isq = latency of onset of the incorrect squeeze response; Iemg = latency of onset of the incorrect EMG response.)

This document is copyrighted by the American Psychological Association or one of its allied publishers.
This article is intended solely for the personal use of the individual user and is not to be disseminated broadly.

the onset latency of the incorrect squeeze (396 ms) was shorter than that of the correct squeeze (501 ms), $F(1, 10) = 79.57$, $p < .001$. This result indicates that even though both squeeze responses are executed, they are not executed simultaneously—the incorrect response occurs first.

Together, these data suggest the following picture: (a) Both response channels may be activated on the same trial; (b) if this activation reaches the level of a squeeze, the two response channels inhibit each other (response competition); (c) response activation is not an all-or-none phenomenon—rather, several levels of activation are possible; (d) the activation of the correct response to the threshold for squeeze emission may occur after the emission of an incorrect squeeze, but the converse is not true.

The latency of the P300 component of the ERP also increases monotonically from N, to E, to S, to Error categories. The results of the relevant ANOVAs are shown in Table 1.[5] Because we interpret the latency of the P300 as a measure of the duration of evaluation processes, we infer that there is an association between the duration of evaluative processes and the likelihood of incorrect activity (at least at the squeeze level). Although this is only a correlational finding, it may suggest that a slowing of the stimulus evaluation process enhances the probability of the appearance of incorrect motor activity. We shall return to this point later.

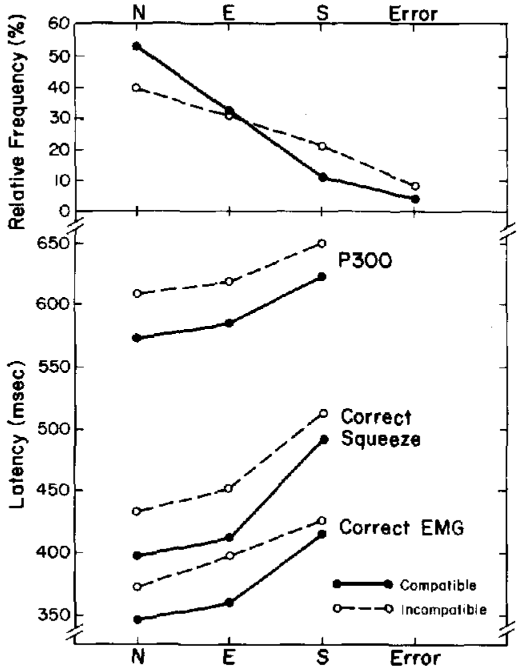

Figure 5. Latency of onset in milliseconds of correct electromyogram (EMG) and squeeze activity and of P300 as a function of response category for compatible and incompatible arrays. (The relative frequencies of each response category for compatible and incompatible arrays are shown in the upper panel.)

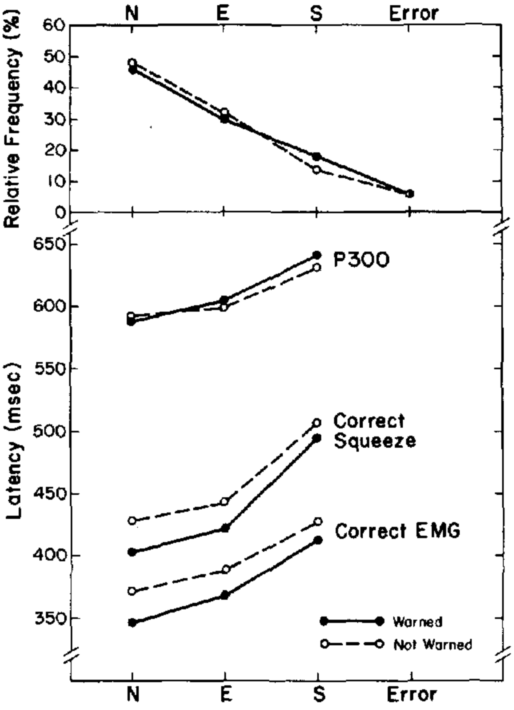

Figure 6. Latency of onset in milliseconds of correct electromyogram (EMG) and squeeze activity and of P300 as a function of response category for warned and not warned trials. (The relative frequencies of each response category for warned and not warned trials are shown in the upper panel.)

b. *Noise/compatibility effect.* Inspection of the distribution of trials according to response category (see Figures 3 and 5) reveals that more trials were classified as N and fewer as S and Error when the noise was compatible. This was confirmed by an ANOVA on transformed (arcsine) percentage values for the E, S, and Error categories, which gave a significant main effect

---

[5] Tukey HSD tests revealed that the differences between E and S were significant. The N and Error categories were not statistically distinguishable from the E and S categories, respectively.

This document is copyrighted by the American Psychological Association or one of its allied publishers.
This article is intended solely for the personal use of the individual user and is not to be disseminated broadly.

Table 1
Results of Analyses of Variance on Latency Measures

Main effect & response side	EMG onset latency *df*	EMG onset latency *F*	Squeeze onset latency *df*	Squeeze onset latency *F*	P300 latency *df*	P300 latency *F*
Noise[a]					1, 10	26.44**
Incorrect	1, 10	8.87*	1, 10	17.94**		
Correct	1, 10	17.13**	1, 10	67.67**		
Warning[a]					1, 10	1.00
Incorrect	1, 10	5.78*	1, 10	9.32**		
Correct	1, 10	8.81*	1, 10	16.44**		
Blocking[a]					1, 10	12.19**
Incorrect	1, 10	4.75	1, 10	2.90		
Correct	1, 10	6.32*	1, 10	4.98		
Response category[a]					2, 20	17.13**
Incorrect	1, 10	26.60**				
Correct	2, 20	51.80**	2, 20	109.24**		
Response category[b]					3, 9	10.61**
Incorrect	2, 6	9.10*	1, 3	23.47*		
Correct						

Note. EMG = electromyogram.
[a] Analysis based on 11 subjects.
[b] Analysis based on 4 subjects.
* $p < .05$. ** $p < .01$.

of noise, $F(1, 10) = 22.13$, $p < .001$, and a significant Noise × Response Category interaction, $F(2, 20) = 8.52$, $p < .01$. Note that these data are consistent with the "traditional" error rate analysis described earlier. However, they provide the important additional information that trials with both squeeze responses were more common when the array was incompatible.

These results confirm the previous findings of Eriksen et al. (in press) and are consistent with the continuous flow model. Evidence for the incorrect response is present in the incompatible array, and this evidence appears to lead to the activation of the incorrect response even though a correct response may be given ultimately.

As we noted above, there were more S trials and fewer N trials when the array contained incompatible noise. Furthermore, in the previous section we saw that response competition occurs on S trials. This is suggested by the delay in both the initiation and execution of the correct response on these trials. Thus, one way in which incompatible noise delays the average RT is by increasing the number of trials on which response competition occurs. If one computes RT without regard to response category (as we did in our initial RT analysis and as would be done in a traditional analysis), the cost of incompatible noise is 47 ms. The larger frequency of S trials for incompatible noise arrays (23%) than for compatible noise arrays (11%) accounts for an effect of 10 ms. This value is derived by weighting mean squeeze latency values for N, E, and S categories by the proportion of trials that were classified in each category. This leaves a 37-ms effect of noise/compatibility that is not yet explained.

Now, even when the level of incorrect response activation is controlled (that is, response category is a factor in the ANOVA), the interval between EMG and squeeze onset in the correct channel is still longer for incompatible noise arrays (67 ms) than for compatible noise arrays (59 ms), $F(1, 10) = 5.31$, $p < .05$. That is, *within* N, E, and S categories the interval between correct EMG and squeeze onset is, on the average, 8 ms longer for incompatible noise arrays. If this value is recomputed on the basis of appropriately weighted means (see above), then the value is 12 ms. Thus, we find an effect of noise/compatibility on the temporal aspects of correct response execution, even when the presence of incorrect activity is controlled. If it is assumed that a prolongation of the interval between EMG and squeeze onset is a sign of response competition, then response compe-

This document is copyrighted by the American Psychological Association or one of its allied publishers.
This article is intended solely for the personal use of the individual user and is not to be disseminated broadly.

tition must have an effect on correct response execution that is not associated with the peripheral activation of the incorrect response channel (i.e., muscle and squeeze activity). This implies that response competition can occur when the activation of the incorrect response channel is below the threshold required for EMG or squeeze activity. Thus, of the 47-ms weighted mean effect of noise/compatibility on correct squeeze response latency, 10 ms can be attributed to a form of response competition that is associated with the emission of an incorrect EMG and squeeze response, and a further 12 ms to a form of response competition that is associated with subthreshold incorrect response activation. This leaves 25 ms to be explained.

The previous analyses indicated that the interval between EMG and squeeze onsets is affected by noise/compatibility. However, the *onset latency* of the correct EMG activity is also affected by noise/compatibility. In fact, the EMG onset latency is 28 ms longer for incompatible noise arrays than for compatible noise arrays even when response category is considered as a factor in the ANOVA. (See Table 1 for the results of ANOVAS and Figures 4 and 5 for the means.) Can this effect also be explained in terms of response competition? To answer this question, we need to examine the P300 data to determine whether noise compatibility affects stimulus evaluation. These data reveal that indeed, stimulus evaluation is longer for incompatible arrays, because the latency of the P300 is delayed. (See Table 1 for results of the relevant ANOVAS.) In fact, the delay in P300 associated with incompatible noise is 32 ms for an unweighted means analysis while the corresponding weighted mean value is 27 ms.[6] The latter value is very close to the 25-ms effect of noise/compatibility that remained after the effects of response competition had been removed.

This series of analyses reveals that the prolongation in the overt response latency for incompatible noise trials (47 ms) is due both to a slowing down of the evaluation process (27 ms) and to an increase in response competition (22 ms). The discrepancy of 2 ms is within the limits of rounding errors. A continuous flow model accounts for this dual effect in terms of the same cause: Incompatible noise produces conflict in stimulus evaluation, which slows the evaluation process *and* activates both response channels, which in turn results in response competition.

This is not the whole picture, however. Subjects also make incorrect responses and exhibit activity on the incorrect side on *compatible* trials, when there is nothing in the stimulus array to activate the incorrect side. This observation suggests the operation of another response-driving process that is independent of the stimulus. This is the process we have labeled *aspecific priming.*

c. *Warning effect.* We expected the process of aspecific priming to be more evident under warned conditions, because of the hypothesized increase in indiscriminant response activation resulting from the warning tone. Indeed, there was a tendency for fewer trials to be classified as N, and more as S, when the warning tone was presented, although the Warning × Category interaction was not significant.

The presence of an uninformative warning tone results in faster motor responses (as shown by EMG and squeeze onset latencies), both for the correct and the incorrect side. However, the latency of P300 is not affected by the warning manipulation (see Table 1 for the results of the corresponding ANOVAS). Furthermore, the interval between the onset of correct EMG activity and the peak of the P300 is longer in the warned condition, $F(1, 10) = 10.22$, $p < .01$. Together, these findings indicate that the warning facilitates motor responses without influencing the speed of evaluation processes. Recall that the presence of the warning tone also affects the number of trials with incorrect squeeze activity (although not significantly). Thus, the presence of the warning tone induces the subjects to respond faster but at a slightly higher error rate.[7] This effect of warning may

---

[6] A similar analysis of P300 latency for the count task, when no overt motor response was required, also revealed a significant main effect of noise, $F(1, 11) = 11.90$, $p < .01$. P300 latency was 16 ms longer for incompatible arrays.

[7] We have argued that the presence of a warning tone does not affect the evaluation process. Rather it leads subjects to become less conservative—they respond faster and make more errors. One apparently troubling aspect of the data is the lack of a significant effect of warning on error rate. Analysis of speed–accuracy trade-off functions such as those presented in Figure 9, Panel c, indicates that a 20-ms decrease in RT (the mean effect of warning) should be associated with an increase in error rate of approximately 3%. This was, in fact, the increase in error rate

be attributed to a greater aspecific priming or to lower response criteria.

Note that the warned condition was characterized by the presence of a negative-going potential (CNV) in the interval between the warning tone and the stimulus array (see Figure 1). Several investigators have related similar scalp negativities to motor preparation (see Deecke, Bashore, Brunia, Grunewald-Zuberbier, Grunewald, & Kristeva, 1984, for a review). Furthermore, some researchers (e.g., Gaillard, 1977; Kok, 1978; Rohrbaugh & Gaillard, 1983; Rohrbaugh, Syndulko, & Lindsley, 1976) have argued that later aspects of the CNV are related to motor preparation. In this sense, then, the late CNV may be a manifestation of aspecific priming.

d. *Effect of blocking.* When the level of noise was fixed rather than random within a block of trials, onset latencies of both EMG and squeeze responses on the correct side and of P300 were significantly shorter (by 17 ms, 15 ms, and 14 ms, respectively). (See Table 1 for the results of ANOVAs and Figure 4 for the means.) These data suggest that stimulus evaluation processes are faster when the level of noise is fixed. For *both* noise/compatibility conditions, it is apparently easier for subjects to perform the task when they know in advance what kind of noise will be presented.

However, there is more to the blocking manipulation than a simple main effect on stimulus evaluation. When we consider the distribution of trials across the different response categories, we find that the effect of fixing the level of noise was different for the different noise/compatibility conditions, $F(2, 20) = 3.84$, $p < .05$. Subsequent analyses revealed that for the fixed compatible noise condition, fewer trials were classified as N and more as S than for the random compatible condition. On the other hand, for incompatible conditions, fixing the level of noise did *not* lead to a larger frequency of S trials. These data confirm our previous conclusion that subjects adopt a less conservative strategy when they are confronted with the fixed compatible condition. Thus, the effect of fixing the level of noise is to speed evaluation processes for both noise/compatibility conditions and to change response strategy when the noise is compatible.

Speed–Accuracy Trade-Off Functions

Up to this point, we have considered the effects of the manipulations on the average duration of the stimulus evaluation process. In this section, we examine speed–accuracy trade-off functions for the various conditions of the experiment. We will show (a) that the noise/compatibility manipulation affects the time course of evidence accumulation, (b) that the warning does not affect the evaluation process, and (c) that fast responses are mainly controlled by the letters flanking the target.

The speed–accuracy functions are obtained by plotting response accuracy as a function of response latency. They are intended to provide a representation of the manner in which stimulus evaluation processes proceed over time that is uncontaminated by response bias factors (e.g., Pachella, 1974). However, as we have noted, this interpretation is predicated on the assumption that the speed of stimulus evaluation processes is constant for a given condition. This assumption may not be valid (see Meyer & Irwin, 1982). Thus, in the analysis reviewed here, we compute *separate* speed–accuracy trade-off functions for trials with *different* durations of stimulus evaluation. We do this by using P300 latency as a parameter. That is, trials are first sorted according to the latency of the P300. Then, for each P300 latency bin, we plot response accuracy against response latency.

We obtained our functions in the following way. First, for each of the 12 subjects, and for each of the eight conditions, the latency of the onset of first EMG response, the correctness of that response, and the P300 latency for each trial were tabulated. Second, we defined each trial as a fast or slow P300 trial if P300 latency on that trial was longer or shorter than the median P300 latency for that subject and condition. We also classified the trials into four quartiles on the basis of EMG onset latency

---

when computed using the definition of an error described in this section. Because error rate was computed on a relatively small number of trials, our estimate was not sufficiently reliable to permit a 3% difference to be significant in an ANOVA. If more reliable estimates were obtained, we could determine whether the difference is "real" or whether, in fact, the subjects are able to respond faster, but at the same accuracy level, when a warning is present. If this is the case, then the effect of the warning might be to change the slope of the response activation function, that is, to speed motor processes.

This document is copyrighted by the American Psychological Association or one of its allied publishers.
This article is intended solely for the personal use of the individual user and is not to be disseminated broadly.

This document is copyrighted by the American Psychological Association or one of its allied publishers.
This article is intended solely for the personal use of the individual user and is not to be disseminated broadly.

for that subject and condition. In this way, trials were sorted into eight groups on the basis of P300 latency (fast/slow) and quartile. For each of these groups, accuracy was computed by dividing the number of correct trials by the total number of trials for that group.

We should note that we use EMG onset latency, rather than squeeze latency, as our measure of response speed in these analyses because the activity in the EMG channel occurs first and is a more sensitive sign of response activation.

Figures 7 and 8 display the speed–accuracy functions for each condition of the experiment for fast and slow P300 latency trials separately. The standard errors for each mean are also shown. Figure 9 displays a summary of the speed–accuracy trade-off functions for different P300 latencies and for the two noise and the two warning conditions. Figures 7, 8, and 9 (Panel a) reveal two important points. First, accuracy increases as EMG latency increases, regardless of the latency of the P300 (i.e., the duration of stimulus evaluation); that is, the slower the response, the more likely it is to be correct, $F(3, 33) = 101.55$, $p < .01$. Second, accuracy is lower for all response speeds when P300 latency is long, $F(1, 11) = 39.99$, $p < .01$. Furthermore, *similar* levels of accuracy are achieved either by the conjunction of a slower EMG response and a slow P300 or by a faster EMG response and a fast P300. In other words, P300 latency, and by implication stimulus evaluation time, appears to determine the relative position of the speed–accuracy trade-off function. Together, these data suggest that the accuracy of a response depends on its timing relative to the evaluation process. When

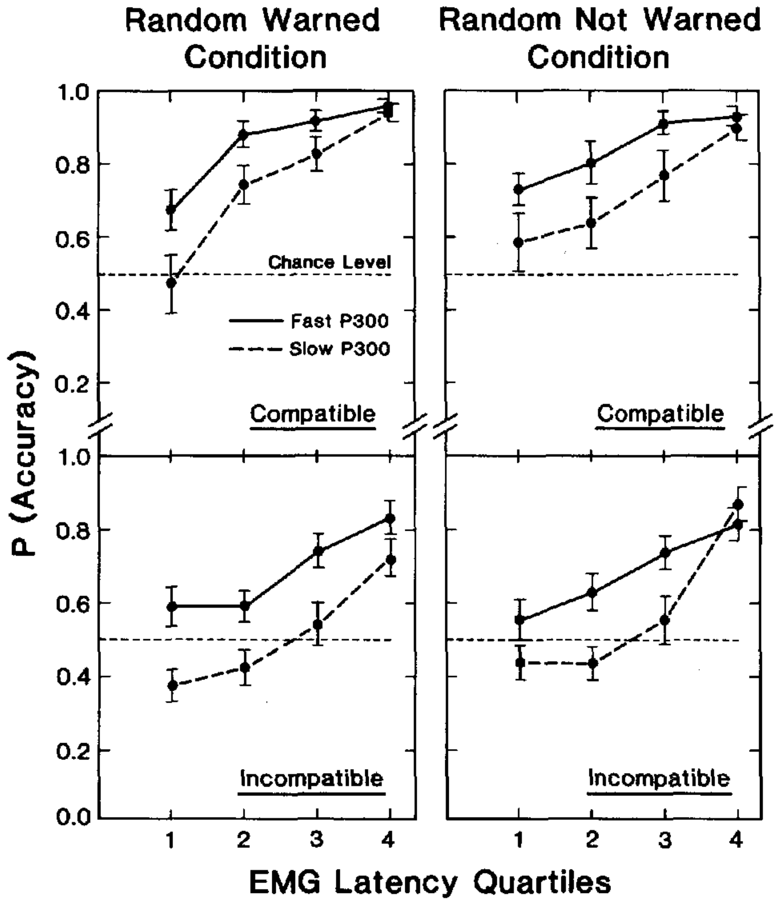

Figure 7. Speed–accuracy trade-off curves as a function of P300 latency for compatible and incompatible noise trials, when noise was randomized within trial blocks, for the two warning conditions separately.

This document is copyrighted by the American Psychological Association or one of its allied publishers.
This article is intended solely for the personal use of the individual user and is not to be disseminated broadly.

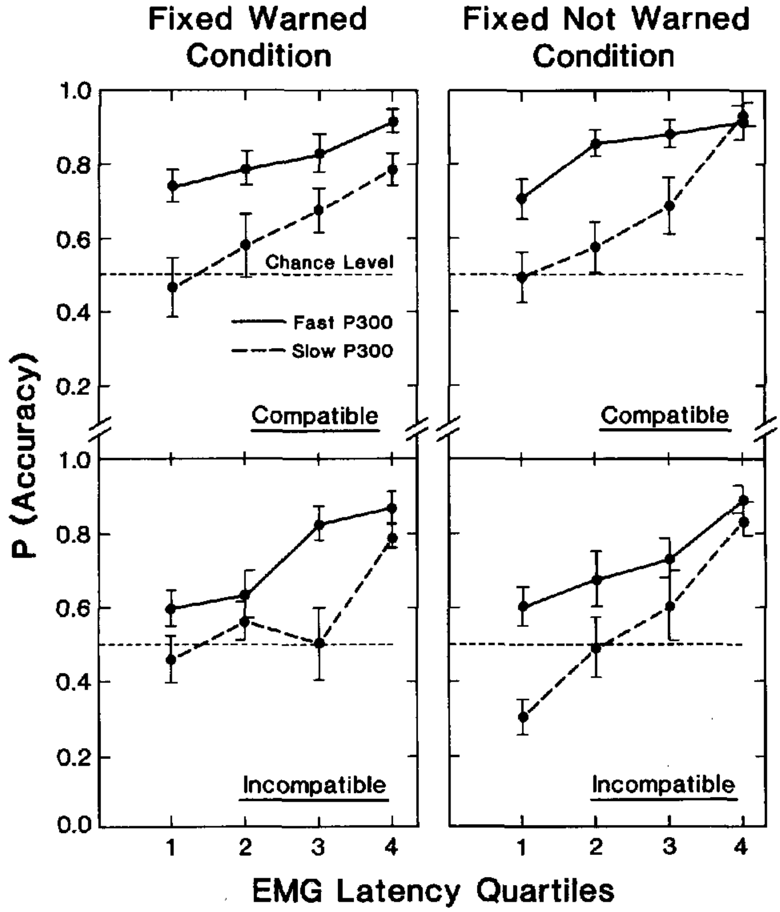

Figure 8. Speed–accuracy trade-off curves as a function of P300 latency for compatible and incompatible noise trials, when noise was fixed within trial blocks, for the two warning conditions separately.

evaluation proceeds quickly, a high level of accuracy is achieved even when responses are fast; conversely, when evaluation proceeds slowly, a high level of accuracy is achieved only when RTs are long.[8] These data illustrate how measures of the P300 can be used to overcome the difficulties raised by the assumption that the duration of the evaluation process is constant on every trial.

Figures 7, 8, and 9 (Panel b) show that speed–accuracy functions for compatible and incompatible noise arrays are different. For each quartile, accuracy is lower for the incompatible arrays, $F(1, 11) = 56.98$, $p < .01$. This confirms that the evaluation process is slower, or at least different, for these arrays.

Figures 7, 8, and 9 (Panel c) show that the functions for warned and unwarned trials are

---

[8] We have interpreted the interaction among P300, EMG onset latency, and accuracy in terms of an effect on accuracy of the relative time during the evaluation process at which a response is emitted. When subjects respond quickly and evaluation is slow, they are likely to make errors. Note that we are inferring that accuracy is a function of P300 and EMG onset latency, although our data are correlational in nature. An alternative interpretation is that the P300 is delayed when the subject makes an error. In fact, we have evidence from another experiment (Gratton, Dupree, Coles, & Donchin, 1985) that P300 can be actively delayed by a process of error recognition. The conditions under which this result was obtained involved a choice RT task under speed instructions. The instructions led the subjects to respond very quickly and at a low accuracy level. As we have outlined elsewhere (Coles, Gratton, & Donchin, 1984), these two interpretations can be distinguished on the basis of the accuracy level for trials on which responses are fast and P300 latency is long. In particular, accuracy should be close to zero for these kinds of trials if the error recognition interpretation is valid. Such a finding

This document is copyrighted by the American Psychological Association or one of its allied publishers.
This article is intended solely for the personal use of the individual user and is not to be disseminated broadly.

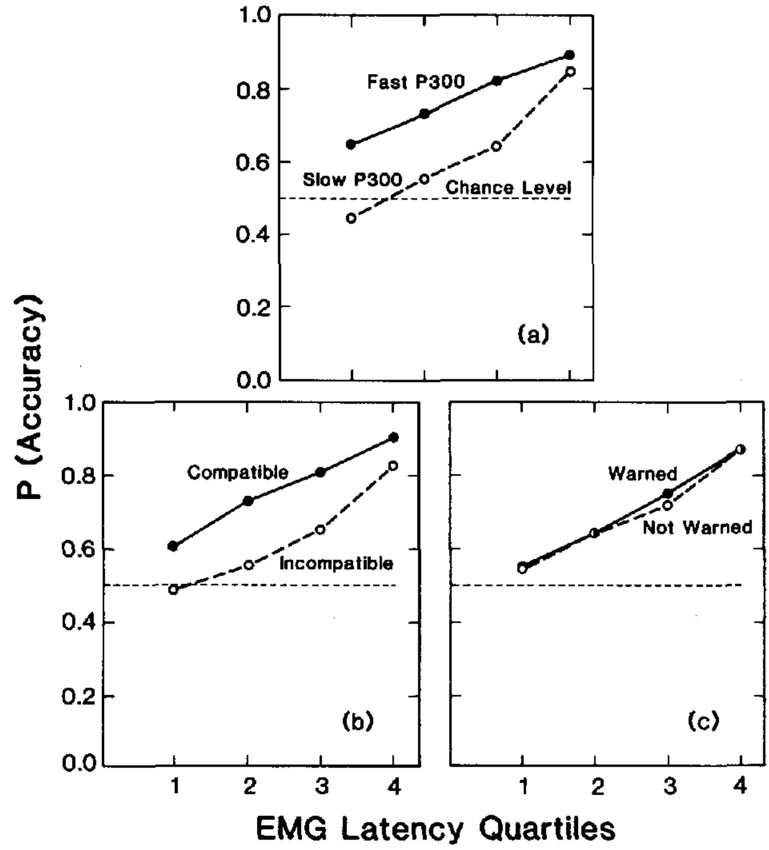

Figure 9. Speed-accuracy trade-off curves as a function of P300 latency (Panel a), noise (Panel b), and warning (Panel c).

essentially identical. For the main effect of warning, $F(1, 11) = 0.19$, $p = 0.67$; for the Warning × Quartile interaction, $F(3, 33) = 0.56$, $p = 0.65$. These observations confirm the conclusion we drew earlier that the presence of a warning stimulus does not affect the evaluation process. Rather, the difference between these two conditions in mean response latencies and error rates reflects a difference in the average point on the speed–accuracy trade-off function at which the subject is operating. As we argued above, the greater aspecific priming (or a lower criterion) on warned trials leads to a less conservative response (i.e., responses are released on the basis of less information).

A further interesting aspect of the functions shown in Figures 7 and 8 concerns the accuracy for fast EMG responses and slow P300s. In the compatible noise conditions, accuracy is approximately 50%. We infer from this that when subjects respond quickly on trials where the duration of stimulus evaluation is long (P300 latency is long), they are essentially guessing. However, on incompatible trials, the combination of fast EMG responses (the first quartile) and slow P300s (across warning and blocking conditions) is associated with an accuracy value that is *below* chance, $t(11) = 3.83$, $p < .01$.

One explanation for this excessive error rate is that early in the evaluation of an incompatible noise array, there is more evidence for the incorrect response. It should be recalled that

---

was obtained in the Gratton et al. (1985) study. However, in the present experiment, the accuracy level for fast response/slow P300 trials is close to 50%. We do find that accuracy level falls below 50% in the incompatible noise condition, but this finding is most readily explained in terms of the potency of the flanking noise in driving the incorrect response.

This document is copyrighted by the American Psychological Association or one of its allied publishers.
This article is intended solely for the personal use of the individual user and is not to be disseminated broadly.

an incompatible array contains one letter associated with the correct response and four letters associated with the incorrect response. Thus, when the subject responds quickly and evaluation is proceeding slowly, the evidence available at the time of response favors the incorrect response. Note that this excessive error rate is not seen in the data for compatible arrays. Our data suggest, then, that early in the evaluation process, the subject performs an analysis of the features of *all* the letters in the array without selecting the information provided by the target letter in the central location. We refer to this process as *feature,* or *letter,* analysis. Selection for the features of the center letter (*location* analysis) appears to occur later. These two aspects of stimulus evaluation, feature, or letter, analysis and location analysis, can both activate the response channels directly. The two processes may occur in sequence or in parallel. However, in the latter case, feature analysis should be faster than location analysis. Thus, fast responses, based mainly on the feature analysis, are likely to be incorrect for an incompatible noise trial, but correct for a compatible noise trial. The process of aspecific priming, discussed earlier, also controls activation of response channels. If one or other of the responses is heavily primed (for example, because of guessing), then that response may be released without being influenced by either feature or location analyses.

Conclusions

The results of this experiment clearly indicate that both the correct and incorrect response channels can be activated concurrently. The activation of the response channels occurs in a graded fashion, so that partial response activation of one response channel may accompany complete response activation of the other channel. When both response channels are activated, *response competition* occurs, and the temporal characteristics of correct response execution are affected. Response activation itself appears to be controlled by two processes: stimulus evaluation *and* aspecific priming. The influence of the first process increases over time after array presentation, because slower responses are more accurate. Furthermore, when the array contains information calling for the incorrect response, this response is more likely to be activated. In fact, when subjects respond early, the incorrect information dominates to such an extent that error rates are greater than chance. The second process, aspecific priming, results in an activation of response channels that is independent of the stimulus. This is evident from the fact that activation of the incorrect response is observed when there is no corresponding information in the stimulus array.

This picture is consistent with the continuous flow model proposed by Eriksen and Schultz (1979). Although it was not the purpose of this study to address the question of the viability of serial stage models, our data are not easily accommodated by a strictly serial stage model (e.g., Sternberg, 1969). For example, to account for our observation of concurrent activation of both response channels, a serial stage model would have to assume that a decision stage emits an output to each of the response channels that is proportional to the evidence accumulated at the moment of the decision.[9] However, this would be inconsistent with the observed temporal relations between the correct and the incorrect responses when both occur on the same trial (the S category). In fact, the incorrect response occurs *before* the correct response on S trials. To explain this finding, one would have to assume several decision stages. Thus, although it is possible to increase the complexity of a serial stage model to account for our data, it is clear that the continuous flow model (and other parallel models) provides a more parsimonious explanation.

The analysis of the EMG and subthreshold squeeze data have important implications for the concept of response competition. First, we find that when incorrect squeeze activity is present, initiation of correct activity is delayed. Second, we find that the temporal characteristics of correct response execution are affected by the degree to which incorrect activity is present. When an incorrect squeeze response is produced (the S category), the interval between correct EMG onset and correct squeeze onset is increased. Finally, when there is evidence in the array for both responses (incompatible condition), this interval is also prolonged, although there may be no peripheral manifestation of activation of the incorrect response (as in the N category). Together, these

---

[9] This model was suggested by an anonymous reviewer.

This document is copyrighted by the American Psychological Association or one of its allied publishers.
This article is intended solely for the personal use of the individual user and is not to be disseminated broadly.

findings are most readily explained in terms of the operation of a response competition mechanism. Furthermore, the fact that the temporal characteristics of response execution can be modified and that responses can be initiated without being executed, suggests that response execution is best conceived of as a continuous process. This view contrasts with that of McClelland (1979), for whom response execution is the only discrete process in the human information processing system.

The manipulations we used in our experiment have different effects on the information processing system. One effect of introducing incompatible *noise* to the stimulus array is to increase the number of trials on which incorrect activity occurs. In general, the presence of incorrect activity is associated with an increase in the time taken to execute a correct response. Thus, the mean RT difference between compatible and incompatible noise is due, at least in part, to response competition. However, the effect of incompatible noise is also to slow down the evaluation process, as indexed by P300 latency. Thus, the noise/compatibility effect on mean RT appears to be due both to an effect on the incidence of response competition *and* to an effect on the stimulus evaluation process.

In contrast to the noise manipulation, the *warning* conditions provided a clear dissociation between P300 latency and the latency of motor response measures (correct and incorrect squeeze and EMG onset latencies). The latter were in fact shortened by the warning, whereas the presence of a warning had no effect on P300 latency. This result suggests that the warning did not influence stimulus evaluation processes, but it was clearly effective in increasing the aspecific priming of the two response channels. These data contrast in an interesting manner with the results of Duncan-Johnson and Donchin (1982). These investigators presented imperative stimuli that either matched or failed to match an antecedent warning stimulus. When the stimuli mismatched, the P300 latency to the imperative stimulus increased. Thus, there are conditions in which the information carried by a warning stimulus can affect the duration of stimulus evaluation processes for a subsequent event, suggesting the operation of *perceptual* priming. However, in the present study, the warning stimulus (a tone) did not match the imperative stimuli (letters). Under these circumstances, there is apparently no opportunity for an effect of perceptual priming on the evaluation process.

By *fixing* the level of noise within a block of trials, correct responses were speeded and P300 latency was shortened. This indicates that fixing the level of noise facilitates the stimulus evaluation process. However, this manipulation also leads to a modification in the response criterion or to a greater aspecific priming in the compatible noise condition, so that subjects respond faster but less accurately.

Insights into the nature of the stimulus evaluation process were provided by the speed–accuracy trade-off functions with stimulus evaluation time controlled. These functions suggest that in our experiment the stimulus evaluation process consists of at least two subprocesses, feature or letter analysis and location analysis. Note that our conception of the process of stimulus evaluation is similar to that discussed by Treisman and her colleagues (Treisman & Gelade, 1980; Treisman, Sykes, & Gelade, 1977). They argue that an early, parallel process of feature analysis precedes the detection of the feature location. Our data suggest that the output of the feature analysis should be available before that of the location analysis, although these two subprocesses may occur in sequence or in parallel. Both feature (letter) and location analyses appear to activate the response channels directly. In fact, the speed–accuracy functions for incompatible arrays reveal that early responses are driven more by the lateral letters than by the central target letter. This short cut of the information processing flow is inconsistent with the assumptions of a strictly serial *and* a strictly cascade model (e.g., McClelland, 1979). Both these models assume that the flow of information proceeds through an ordered sequence of processing elements. On the other hand, these kinds of short cuts are not inconsistent with the assumptions of the continuous flow model (Eriksen & Schultz, 1979).

An interesting integration of serial and parallel models has been proposed recently by Miller (1982, 1983). His model can be described as a hybrid *parallel–discrete* model. He suggests that information is *not* transferred continuously between processing elements. Rather, the transfer occurs only when an element has completely processed a "grain" of

This document is copyrighted by the American Psychological Association or one of its allied publishers.
This article is intended solely for the personal use of the individual user and is not to be disseminated broadly.

information. Thus, information represented by a grain is transferred discretely. However, when there is more than one grain, different processing elements can be engaged in parallel. Note that, when all the relevant information is contained in one grain, his model is formally equivalent to a serial model. When the relevant information can be partitioned into an infinite number of grains, his model is formally equivalent to a cascade model. In terms of Miller's model, our data suggest that the information is partitioned into more than one grain, because responses are activated on the basis of partial information about the stimulus array. Furthermore, at the level of feature (or letter) analysis, several grains must be handled in parallel. On the other hand, at the level of location analysis information may be transferred in only one grain.

In summary, the results of our experiment are consistent with the continuous flow model (Eriksen & Schultz, 1979), although they are not inconsistent with other parallel models, such as those proposed by Miller (1982) or Grice and his colleagues (Grice et al., 1977, 1982). We have provided evidence for two relatively independent sources of response activation: an aspecific, stimulus-independent process, and a specific, stimulus-dependent process. As evidence accumulates in the stimulus evaluation system, specific activation of the associated response systems occurs. Activation of the incorrect channel is determined both by the amount of aspecific priming and by the evaluation process, when there is evidence in the stimulus for the incorrect response. Activation of the incorrect response channel can interfere with correct response execution through a response competition process.

References

Brookhuis, M. A., Mulder, G., Mulder, L. J. M., & Gloerich, A. B. M. (1983). The P3 complex as an index of information processing: The effects of response probability. *Biological Psychology, 17,* 277–296.

Coles, M. G. H., Gratton, G., & Donchin, E. (1984, September). *Flies in the ointment.* Paper presented at the IIIrd International Conference on Cognitive Neuroscience, Bristol, England.

Deecke, L., Bashore, T., Brunia, C. H. M., Grunewald-Zuberbier, E., Grunewald, G., & Kristeva, R. (1984). Movement-associated potentials and motor control. In R. Karrer, J. Cohen, & P. Tueting (Eds.), *Brain and information: Event-related potentials* (pp. 398–428). New York: New York Academy of Sciences.

Donchin, E. (1979). Event-related brain potentials: A tool in the study of human information processing. In H. Begleiter (Ed.), *Evoked potentials and behavior* (pp. 13–75). New York: Plenum Press.

Donchin, E. (1981). Surprise! . . . Surprise? *Psychophysiology, 18,* 493–513.

Donders, F. C. (1969). On the speed of mental processes. In W. G. Koster (Ed. and trans.), *Attention and performance II* (pp. 412–431). Amsterdam: North-Holland.

Duncan-Johnson, C. C., & Donchin, E. (1977). On quantifying surprise: The variation of event-related potentials with subjective probability. *Psychophysiology, 14,* 456–467.

Duncan-Johnson, C. C., & Donchin, E. (1982). The P300 component of the event-related brain potential as an index of information processing. *Biological Psychology, 14,* 1–52.

Duncan-Johnson, C. C., & Kopell, B. S. (1981). The Stroop effect: Brain potentials localize the source of the interference. *Science, 214,* 938–940.

Eriksen, C. W., Coles, M. G. H., Morris, L. R., & O'Hara, W. P. (in press). An electromyographic examination of response competition. *Bulletin of the Psychonomic Society.*

Eriksen, B. A., & Eriksen, C. W. (1974). Effects of noise letters upon the identification of a target letter in a nonsearch task. *Perception & Psychophysics, 16,* 143–149.

Eriksen, C. W., & Eriksen, B. A. (1979). Target redundancy in visual search: Do repetitions of the target within the display impair processing? *Perception & Psychophysics, 26,* 195–205.

Eriksen, C. W., & Schultz, D. W. (1979). Information processing in visual search: A continuous flow conception and experimental results. *Perception & Psychophysics, 25,* 249–263.

Fabiani, M., Gratton, G., Karis, D., & Donchin, E. (in press). The definition, identification, and reliability of measurement of the P300 component of the event-related brain potential. In P. K. Ackles, J. R. Jennings, & M. G. H. Coles (Eds.), *Advances in psychophysiology: Vol. 2.* Guilford, CT: JAI Press.

Ford, J. M., Roth, W. T., Mohs, R. C., Hopkins, W. F., & Kopell, B. S. (1979). Event-related potentials recorded from young and old adults during a memory retrieval task. *Electroencephalography and Clinical Neurophysiology, 47,* 450–459.

Gaillard, A. W. K. (1977). The late CNV wave: Preparation versus expectancy. *Psychophysiology, 14,* 563–568.

Ganz, L. (1975). Temporal factors in visual perception. In E. Carterette & M. P. Friedman (Eds.), *Handbook of perception* (Vol. 5, pp. 169–231). New York: Academic Press.

Gratton, G., Coles, M. G. H., & Donchin, E. (1983). Filtering for scalp distribution: A new approach (vector filter). *Psychophysiology, 20,* 443–444. (Abstract)

Gratton, G., Dupree, D., Coles, M. G. H., & Donchin, E. (1985). *P300 and error processing.* Manuscript in preparation.

Gratton, G., Kramer, A. F., & Coles, M. G. H. (1984). A comparative study of measures of the latency of event-related brain components. *Psychophysiology, 21,* 578–579. (Abstract)

Grice, G. R., Nullmeyer, R., & Spiker, V. A. (1977). Application of variable criterion theory to choice reaction time. *Perception & Psychophysics, 22,* 431–449.

Grice, G. R., Nullmeyer, R., & Spiker, V. A. (1982). Human

This document is copyrighted by the American Psychological Association or one of its allied publishers.
This article is intended solely for the personal use of the individual user and is not to be disseminated broadly.

reaction times: Toward a general theory. *Journal of Experimental Psychology: General, 111,* 135–153.

Grossberg, S. (1982). *Studies of mind and brain: Neural principles of learning, perception, development, cognition, and motor control.* Boston: Reidel Press.

Hoffman, J. E., Houck, M. R., MacMillan, F. W., Simons, R. F., & Oatman, L. C. (1985). Event-related potentials elicited by automatic targets: A dual-task analysis. *Journal of Experimental Psychology: Human Perception and Performance, 11,* 50–61.

Jasper, H. H. (1958). The ten-twenty electrode system of the International Federation. *Electroencephalography and Clinical Neurophysiology, 10,* 371–375.

Karis, D., Fabiani, M., & Donchin, E. (1984). P300 and memory: Individual differences in the von Restorff effect. *Cognitive Psychology, 16,* 177–216.

Kok, A. (1978). The effect of warning stimulus novelty on the P300 and components of the contingent negative variation. *Biological Psychology, 6,* 219–233.

Kutas, M., & Donchin, E. (1977). The effect of handedness, of responding hand, and of response force on the contralateral dominance of the readiness potential. In J. Desmedt (Ed.), *Attention, voluntary contraction and event-related cerebral potentials* (pp. 189–210). Basel: Karger.

Kutas, M., McCarthy, G., & Donchin, E. (1977). Augmenting mental chronometry: The P300 as a measure of stimulus evaluation time. *Science, 197,* 792–795.

Lappin, J. S., & Disch, K. (1972a). The latency operating characteristics: I. Effects of stimulus probability on choice reaction time. *Journal of Experimental Psychology, 92,* 419–427.

Lappin, J. S., & Disch, K. (1972b). The latency operating characteristics: II. Effects of visual stimulus intensity on choice reaction time. *Journal of Experimental Psychology, 93,* 367–372.

Lippold, O. C. J. (1967). Electromyography. In P. H. Venables & I. Martin (Eds.), *A manual of psychophysiological methods* (pp. 245–297). Amsterdam: North-Holland.

Magliero, A., Bashore, T. R., Coles, M. G. H., & Donchin, E. (1984). On the dependence of P300 latency on stimulus evaluation processes. *Psychophysiology, 21,* 171–186.

McCarthy, G., & Donchin, E. (1981). A metric for thought: A comparison of P300 latency and reaction time. *Science, 211,* 77–80.

McClelland, J. L. (1979). On the time relations of mental processes: An examination of systems of processes in cascade. *Psychological Review, 86,* 287–330.

Meyer, D. E., & Irwin, D. E. (1982). *On the time course of rapid information processing* (Tech. Rep. No. 43). Ann Arbor: University of Michigan, Cognitive Science Program.

Miller, J. (1982). Discrete versus continuous stage models of human information processing: In search of partial output. *Journal of Experimental Psychology: Human Perception and Performance, 8,* 273–296.

Miller, J. (1983). Can response preparation begin before stimulus recognition finishes? *Journal of Experimental Psychology: Human Perception and Performance, 9,* 161–192.

Pachella, R. G. (1974). The interpretation of reaction time in information processing research. In B. H. Kantowitz (Ed.), *Human information processing: Tutorials in performance and cognition* (pp. 41–82). Hillsdale, NJ: Erlbaum.

Posner, M. I. (1978). *Chronometric explorations of mind.* Hillsdale, NJ: Erlbaum.

Ragot, R. (1984). Perceptual and motor space representation: An event-related potential study. *Psychophysiology, 21,* 159–170.

Rohrbaugh, J. W., & Gaillard, A. W. K. (1983). Sensory and motor aspects of the contingent negative variation. In A. W. K. Gaillard & W. Ritter (Eds.), *Tutorials in event-related potential research: Endogenous components* (pp. 269–310). Amsterdam: North-Holland.

Rohrbaugh, J. W., Syndulko, K., & Lindsley, D. B. (1976). Brain components of the contingent negative variation in humans. *Science, 191,* 1055–1057.

Sherrington, C. S. (1906). *Integrative action of the nervous system.* New York: Scribner.

Sternberg, S. (1969). The discovery of processing stages: Extensions of Donders' method. In W. G. Koster (Ed.), *Attention and performance II* (pp. 276–315). Amsterdam: North-Holland.

Treisman, A., & Gelade, G. (1980). A feature integration theory of attention. *Cognitive Psychology, 12,* 97–136.

Treisman, A., Sykes, M., & Gelade, G. (1977). Selective attention and stimulus integration. In S. Dornic (Ed.), *Attention and performance VI* (pp. 333–361). Hillsdale, NJ: Erlbaum.

Tukey, J. W. (1953). *The problem of multiple comparisons.* Princeton, NJ: Princeton University Press.

Turvey, M. T. (1973). On peripheral and central processes in vision: Inferences from an information-processing analysis of masking with patterned stimuli. *Psychological Review, 80,* 1–52.

Walter, W. G., Cooper, R., Aldridge, V. J., McCallum, W. C., & Winter, A. L. (1964). Contingent negative variation: An electrical sign of sensorimotor association and expectancy in the human brain. *Nature, 203,* 380–384.

Yeh, Y-Y., & Eriksen, C. W. (1984). Name codes and features in the discrimination of letter forms. *Perception & Psychophysics, 36,* 225–233.

Received December 3, 1984
Revision received April 16, 1985 ■