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# TUTORIALS IN MOTOR BEHAVIOR II

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## Response Activation and Verification: A Psychophysiological Analysis<sup>1</sup>

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### Abstract

In this chapter, we illustrate how psychophysiological measures can be used to illuminate the processes by which responses are selected and activated. We will focus on studies using stimulus-response compatibility and related paradigms. Our data suggest that, when a stimulus-response mapping is incongruent, incorrect responses are activated - although this activation may be insufficient for the elicitation of an overt behavioral response. These findings provide support for the notion of automatic activation of responses that has been incorporated into the model proposed by Kornblum and his colleagues (Kornblum, Hasbroucq, & Osman, 1990; see also Kornblum, this volume). Furthermore, we have recently identified a brain potential component that appears to be a manifestation of the process associated with the detection of erroneous responses. Such a process is also a critical component of the Kornblum model.

### 1. THE PSYCHOPHYSIOLOGICAL APPROACH

Traditional approaches to the study of stimulus-response compatibility (and of mental chronometry in general) have relied on measures of the subject's overt behavior (see, for example, Meyer, Osman, Irwin, & Yantis, 1988 and Proctor & Reeve, 1990). The subject is required to respond overtly to particular events (or imperative stimuli), and measures of the speed and accuracy of these responses are used to make inferences about the covert processes engaged by the task. In contrast, the psychophysiological approach relies on measures of **both** speed and accuracy **and** of psychophysiological function (see Coles, 1989; Coles, Gratton, & Fabiani, 1990; Donchin & Coles, 1989). The idea is that the psychophysiological measures are manifestations of some of the covert processes of interest.

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In our research, we have focussed on measures of the event-related brain potential and of the electromyogram. In a typical experiment, subjects perform a choice-reaction time task (that includes a warning signal on each trial) and they must choose between a response with either their left- or right-hands depending on the imperative stimulus. To register a response, they must squeeze zero-displacement dynamometers, and the force level must exceed a certain criterion, in order for the squeeze is to be registered as a "complete" response. This criterion is usually set at 25% of the maximum force that can be exerted by a subject. Subjects are given extensive training with this procedure. (See Coles, Gratton, Bashore, Eriksen, & Donchin, 1985, for a discussion of this response requirement.)

Along with measures of the subject's squeeze responses, we derive measures of the electroencephalogram (EEG) from various scalp locations. Embedded in these EEG records are the event-related brain potentials (ERPs) that represent neural activity that is time-locked to particular events in the task. The ERPs are generally revealed by averaging the EEG data from many trials. We also record integrated electromyographic activity from the forearm flexors, the agonist muscles involved in executing the squeeze response.

One advantage of using dynamometers is that they can be used to detect responses that do not necessarily reach the criterion for registration as a complete overt response -- that is, we can detect sub-threshold response activation. We have focussed especially on trials where the subjects make **partial** errors. Recall that, in our experiments, subjects are choosing between left- and right-hand responses as a function of an imperative stimulus. Thus, sometimes the left-hand response is correct and the right-hand response is incorrect, and sometimes the opposite is the case. Had we relied strictly on measures of the subjects' overt behavior derived from the usual discrete response manipulandum (i.e., a button or computer key), we could only have identified two kinds of trials in this kind of choice reaction time experiment: **correct** trials, when the subject executes the correct response, and **incorrect** trials when the subject executes the incorrect response. However, our approach allows us to identify trials on which the correct response is executed but the incorrect response is partially activated. This partial activation can be revealed in measures of EMG and of squeeze activity that does not reach the criterion for an overt response. Based on these measures, we have been able to identify two kinds of partial errors: those on which a correct response is executed but incorrect EMG activity is also present without any detectable force being exerted on the dynamometers (partial EMG errors) and those on which a correct response is executed but incorrect EMG and squeeze activity is present (partial squeeze errors).

Measures of partial response activation have enabled us to address a variety of important questions. We will review these shortly. For the time-being, it is important to note that the partial error trials would have been treated as correct response trials, if standard discrete response devices had been used and electromyographic and squeeze activity had not been recorded.

We have also looked at a measure of movement-related brain activity -the *lateralized readiness potential* (LRP) - to evaluate the prevalence of partial response activation in choice reaction time tasks. This measure is sensitive to central response activation processes that do not necessarily reach the level required for peripheral EMG or squeeze activity.

The readiness potential was first described by Kornhuber and Deecke (1965), who observed that a negative potential develops at the scalp prior to the execution of voluntary motor responses. Subsequent research has shown that the potential tends to be larger over the hemisphere contralateral to the responding limb (e.g., Kutas & Donchin, 1980). Furthermore, the scalp distribution of the potential is related to known lateralization in the motor system. This is consistent with our interpretation that the potential can qualify as a measure of motor system activity. This inference is supported by other psychophysiological and neurophysiological research (for review, see Coles, 1989).

One can also observe this lateralized potential in reaction time tasks. Generally speaking, the potential appears to become lateralized when the subject begins to prepare the hand that will be used to execute a response (see Kutas & Donchin, 1980; Rohrbaugh, Syndulko, & Lindsley, 1975). Before subjects execute a left-hand response, the negative potential is larger over the right, than the left, side of the brain: the converse is true for right-hand movements. To focus on preparatory processes associated with specific responses (i.e., hands), we have developed a subtraction and averaging procedure to isolate the lateralized portion of these potentials (see Coles, 1989, for a detailed description of the procedure<sup>2</sup>). The measure yielded by this procedure (the LRP) represents the degree to which the subject has differentially primed one or other of the two responses (hands). In practice, the subtraction is performed separately for trials when a left-hand movement is the correct response and for trials when a right-hand movement is the correct response. The resulting values are then averaged to yield a measure of the degree to which the subject shows lateralization associated with the preparation of the correct or incorrect response. We use the measure, then, to infer whether the subject has preferentially activated the correct or incorrect response, and by what time such preferential activation must have happened.

## 2. THE PSYCHOPHYSIOLOGICAL APPROACH AND STIMULUS RESPONSE COMPATIBILITY

As we noted earlier, there are two aspects of the Kornblum model for which psychophysiological data are particularly relevant (see Kornblum et al., 1990, and Kornblum, this volume, for an elaboration of the model). First, there is the process associated with automatic activation of responses following stimulus presentation. According to Kornblum, this process occurs as a result of the *dimensional overlap* between stimulus and response sets. The presentation of a stimulus automatically primes the corresponding response. When the activated and required responses are the same, the mapping is said to be "congruent" - when they are different, the mapping is "incongruent".

The second process of interest involves the comparison of a representation of the automatically activated response with a representation of the required response.

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<sup>2</sup> Note that the procedure used to derive the LRP is equivalent to that described by de Jong, Wierda, Mulder, & Mulder (1988) to derive their measure of the *Corrected Motor Asymmetry*.

According to the model, if these two representations do not match, then the activated response is aborted.

## 2.1 "Automatic" response activation

### 2.1.1 *The Eriksen Noise Compatibility Paradigm.*

In this paradigm (see Eriksen & Eriksen, 1974), subjects must respond with either the left- or right-hand to stimuli that are comprised of attributes some of which may be mapped to the correct response and some to the incorrect response. On any trial, one of four arrays are presented to the subject. The arrays contain a central target letter and four "noise" letters arranged symmetrically to the left and right of the target letter. Subjects are required to respond with, say, their left-hand if the central target letter is an H, and with their right hand, if the central target letter is an S. Note that, for two of the arrays (referred to by us as "incompatible"), the noise letters are those associated with the incorrect response.

This paradigm is not strictly a "Stimulus-Response Compatibility" paradigm, because there is no dimensional overlap between stimulus and response sets. The dimension of the stimulus set (the letters - H or S) has nothing in common with the dimension of the response set (the response hand - left or right). However, because subjects always make a response with the same hand to a given target letter, it is reasonable to propose that the representations of particular letters come to be associated with particular responses without the need for look-up or search processes. Thus, the letters may, in fact, automatically prime particular responses.

This implies that, when arrays contain noise that is associated with the incorrect response, presentation of the array may lead to the activation of the incorrect response, even though the correct response is eventually executed when the central target letter has been identified. In this sense, the S-R mapping for so-called incompatible arrays may lead to an effect that is analogous to that produced by incongruent S-R mappings when there is dimensional overlap.

Recall that, by recording the EMG and squeeze activity associated with both correct and incorrect responses, we can identify two classes of partial errors: those for which incorrect EMG activity is present and those for which both incorrect EMG and incorrect squeeze activity are present. Data from two experiments in which measures of partial errors have been obtained (Coles et al., 1985; Eriksen, Coles, Morris, & O'Hara, 1985) reveal that partial errors occurred more often when the array contained incompatible noise than when the array was compatible. Thus, even though the noise letters that flanked the target letter were irrelevant to the subject's task, they were evidently processed to the extent of activating the responses associated with them. In this regard, our data are consistent with the idea of automatic activation proposed by Kornblum.

The Kornblum model focusses on those incorrect responses that are activated if the stimulus array contains attributes that are associated with the incorrect response. If this were the only mechanism responsible for incorrect responses, then one would not expect subjects to make partial errors (or indeed any errors) under congruent mapping conditions. However, Coles et al. (1985) found that approximately 45% of compatible trials contained partial errors, mostly involving incorrect EMG activation without

incorrect squeeze activation. We attribute this phenomenon to an aspecific priming process by which subjects prime responses independently of the information provided by the stimulus. Such a process can be triggered by guessing strategies that involve the development of response biases during the foreperiod as well as by "mere presentation" effects, by which responses are indiscriminately activated following stimulus presentation (Coles et al., 1985; Gratton, Coles, Sirevaag, Eriksen, & Donchin, 1988).<sup>3</sup>

Another interesting aspect of the partial error data concerns the temporal dynamics of correct response execution as a function of the activation of the incorrect response. Regardless of the kind of array (compatible or incompatible), the correct response had a longer latency when the incorrect response was partially activated. In addition, the interval between the first sign of correct EMG activity and the first sign of correct squeeze activity was longer under these partial error conditions. Both these observations suggest that correct response activation processes were disrupted when the incorrect response was also activated. These data suggest that at least part of the delay in correct response execution under incongruent mapping conditions may be attributed to a competition between responses that are activated on the same trial.

We have also examined the behavior of the lateralized readiness potential in the Eriksen task. As we noted earlier, this potential is a manifestation of central response activation processes. Figure 1 shows the brain potential data for the compatible and incompatible conditions. In the upper part of the slide, we see averaged data over all trials, including those on which the subjects executed incorrect responses. Note that when the array was incompatible, there is a dip in the lateralized readiness potential shortly after stimulus presentation. This dip indicates that, on the average, at this point in time, the incorrect response was preferentially activated. In the lower part of the figure, we see data for a subset of trials for which the subject responded relatively slowly - that is, they did not guess - and for which there was no evidence in the EMG of incorrect response activation. Notice that the dip in the lateralization function is still evident for the incompatible condition. This suggests that partial incorrect response activation can occur centrally without resulting in any signs of peripheral response activation.

Taken together, then, these data indicate that incorrect responses can be activated in the Eriksen paradigm by the presence of "irrelevant" noise that is associated with the incorrect response. This incorrect response activation can be seen centrally, in the lateralized readiness potential, and more peripherally, in the electromyogram and small overt responses.

### *2.1.2 The Go/No-go paradigm.*

Strictly speaking, the Eriksen paradigm does not qualify as a "Stimulus-Response Compatibility" paradigm because it does not involve dimensional overlap between stimulus and response sets. Furthermore, the "incompatibility" that arises in the Eriksen paradigm is due to a conflict between an **irrelevant** stimulus attribute (the noise) and

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<sup>3</sup> Kornblum (1991, personal communication) also believes that there is a random error producing process of the kind described here. In this regard, it should be noted that the model described in Kornblum et al. (1990) was not intended to provide a general account of errors.

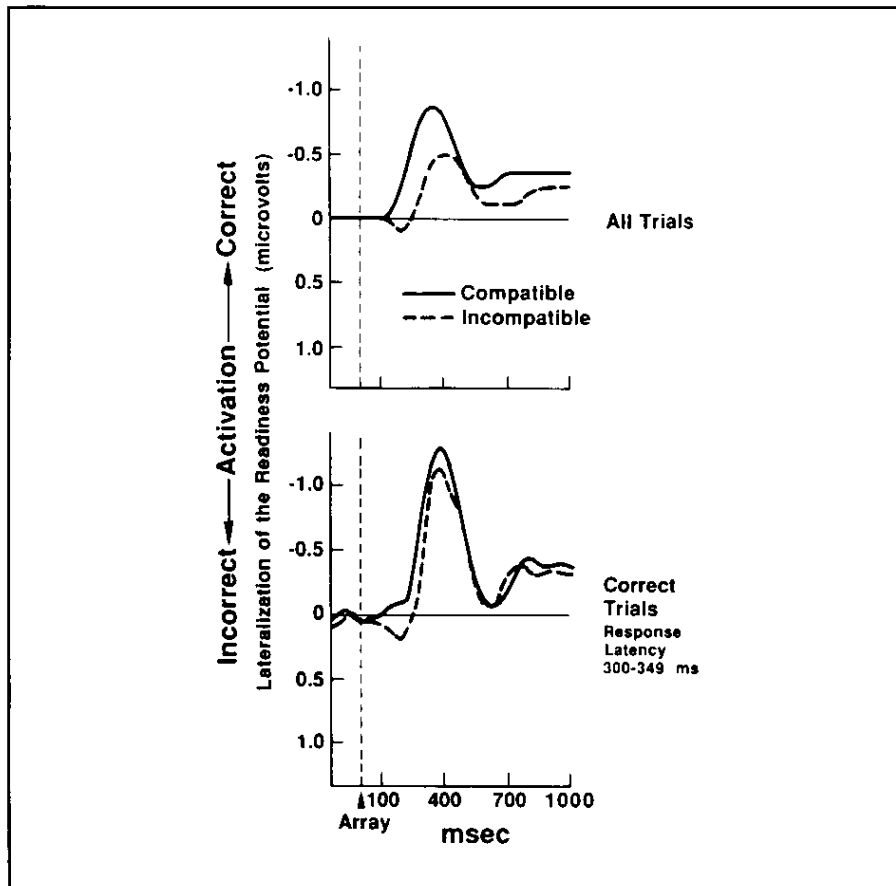


Figure 1. Lateralized readiness potential data for compatible and incompatible trials, from Gratton et al. (1988). Copyright 1988, American Psychological Association, reprinted by permission.

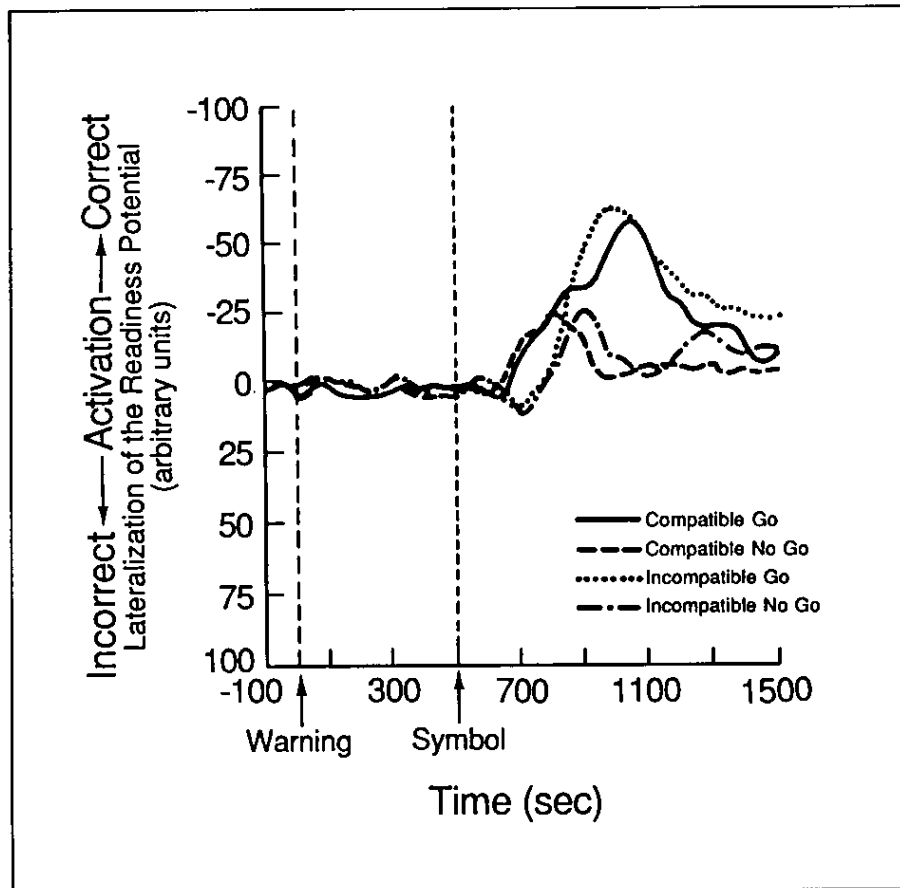
the required response. In a study by Osman and his colleagues (Osman, Bashore, Coles, Donchin, & Meyer, in press) the psychophysiological approach was used to study response processes in a paradigm in which a **relevant** dimension of the stimulus (location on a screen to the left or right of fixation) **did** overlap the response dimension (left or right-hand response). In this task, subjects had to **execute** a response if the stimulus was a letter, but to **withhold** the response if the stimulus was a digit. The stimulus could appear to the left or right of fixation. Under compatible conditions, a stimulus on the left designated a response with the left-hand (if the stimulus was a letter), and a stimulus on the right required a response with the right hand. In incompatible conditions, the mapping was reversed.

For our purposes, the question of interest is whether the incorrect response is automatically activated by the location of the stimulus in the incompatible condition.



Figure 2 shows that there is indeed a dip in the lateralized readiness potential for both go and no-go trials in the incompatible condition.<sup>4</sup>

Thus, as in the Eriksen experiments, psychophysiological data support the proposal that there are conditions under which responses are automatically activated. In the case of the Osman experiment, however, there **was** dimensional overlap between stimulus and response sets and this overlap was between a **relevant** stimulus dimension and the response. Thus, the Osman data perhaps provide even stronger support for the automatic activation process that is an important aspect of the Kornblum model.



**Figure 2.** Lateralized readiness potential data for compatible and incompatible go and no-go trials from Osman et al. (in press). Copyright 1992, American Psychological Association, reprinted by permission.

<sup>4</sup> An analysis of the LRP waveforms, averaged across go and no-go trials for the incompatible conditions, revealed that the waveform in the region between 150 and 250 ms after the stimulus was significantly different from zero ( $t(5) = 2.77$ ,  $p = .039$ ).

### 2.1.3 On the automaticity of "automatic" activation.

The experiments reviewed in the previous two sections suggest that certain stimulus attributes are processed to the level of response activation even though this may result in the activation of the incorrect response. Given that this kind of activation is evidently antithetical to the task requirements placed on the subject for fast and accurate performance, it is tempting to infer that the activation is somehow outside the subject's control -- and in this sense, "automatic".

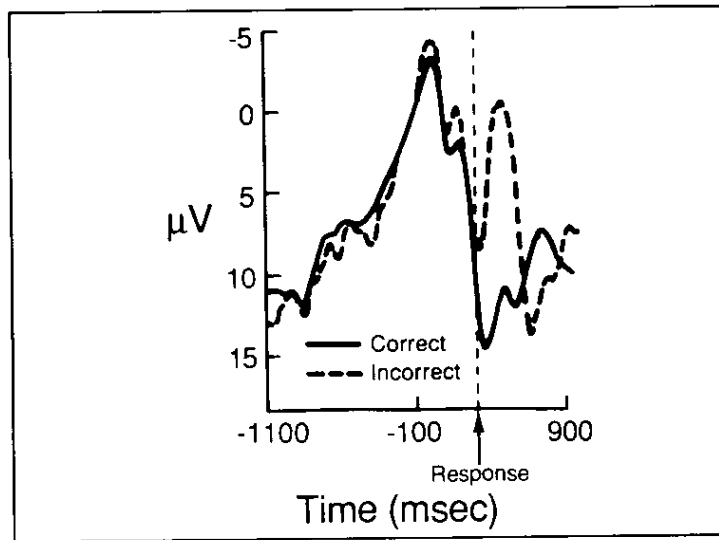
In a recent chapter (Coles, De Jong, Gehring, & Gratton, 1991; see also Coles, Gratton, & Donchin, 1988), we reviewed the results of a variety of reaction time experiments involving stimuli with (at least) two attributes, one of which was easier to discriminate than the other. In all these experiments, the LRP was used to determine whether both attributes were always processed to the level of response activation. While such processing did indeed occur in some experiments, this was not invariably the case. Furthermore, even under those circumstances in which the *same* stimuli were used, but in different task situations, the LRP data revealed that processing of the easier-to-discriminate attribute did not always result in response activation (cf. De Jong et al., 1988; Miller & Hackley, 1990). We interpreted these data as suggesting that the subject can exert control over the degree to which responses are activated following stimulus presentation. To the extent possible, this control will be exercised so as to optimize performance in the context of task goals.

This notion has been examined recently by a series of experiments by Gratton (Gratton, Coles, & Donchin, 1988). The results of these experiments indicate that the effect of noise compatibility in the Eriksen paradigm can be modified when the probability of compatible and incompatible noise is varied. This modification was evident in both overt behavioral and LRP measures and appeared to reflect the actions of a control process that adjusts the degree to which processing of the noise letters leads to response activation. It is clear, then, that the kind of activation observed in the Eriksen paradigm must be "weakly" automatic (cf. Kornblum et al., 1990).

## 2.2 The Verification Process

A second feature of the Kornblum model is a mechanism by which the accuracy of the automatically activated congruent response is verified and the response is aborted, if necessary.

Psychophysiological evidence for the verification process comes from a comparison of the brain potentials that are temporally related to the initiation of correct and incorrect responses. In contrast to the brain potential data discussed previously, these data are derived by using the subject's response as the event of interest rather than the stimulus. Figure 3 shows such a comparison. These data were derived from the Eriksen noise compatibility paradigm described previously. The Figure shows waveforms representing brain potential activity for correct and incorrect trials. In this case, the presence and accuracy of a response was defined by the first "complete" overt response detected. Although we only show data for incompatible trials and for the C3 electrode, comparable differences between correct and incorrect compatible trials are found and similar effects are observed at other electrode locations.



**Figure 3.** The error-related negativity in the Eriksen task. Response-locked averages (for the Cz electrode) for correct and incorrect trials.

The most striking feature of these data is the negative-going potential that begins at around the time that overt response is recorded. Note that the potential is present in both conditions, on both sides of the scalp, and that it is absent on correct trials. The fact that there is a brain process that distinguishes between correct and incorrect responses at about the time of overt response initiation implies the existence of a mechanism that verifies the accuracy of the response before or during response execution. Thus, the presence of this "error-related negativity" provides support for the existence of the kind of verification process that is integral to the Kornblum model.

We have observed the error-related negativity in a number of different choice-reaction time tasks, including Sternberg memory set tasks, precueing tasks, sentence verification tasks, and speed-accuracy tradeoff tasks (see Gehring, Meyer, Coles, & Donchin, 1990). Thus the phenomenon is not dependent on a particular group of subjects, a particular kind of task, or a particular response device (we have used both dynamometers and response buttons). The data, then, suggest that there is a distinct brain response that occurs at about the time subjects make an incorrect motor response. The existence of this response suggests that some part of the system must have representations both of the response being executed and of the response that *should* be executed. Of course, it is the comparison of these representations that is the essence of the verification process.

Another important finding is that the error-related negativity is not lateralized - that is, the distribution of this brain response across the scalp does not depend on the hand used by the subject in making the incorrect response. (Note that this contrasts with the *lateralized readiness potential*.) This suggests that the brain process does not occur in those cortical areas responsible for ultimate control of the movement - or the implementation of an abort process.

From the foregoing it seems clear that the brain process we have observed on error trials is related to a comparison process of the kind proposed by the Kornblum model.

### 2.2.1 *On the need for a response abortion process.*

Kornblum and his colleagues propose that, if the verification process reveals that the incorrect response has been activated, then it must be actively aborted. As we have noted, incorrect responses are activated when the stimulus contains attributes that correspond to the incorrect response. Furthermore, this incorrect response activation can occur at a "subthreshold" level. One interpretation of this finding is that these kinds of partial error trials represent partially successful attempts to abort incorrect responses. Alternatively, they may just represent cases where bias processes and/or the available stimulus information are insufficient to lead to complete response activation - that is, they are "miscarriage" trials rather than partially successful abortion trials. Two arguments favor the latter explanation. First, as we noted earlier, psychophysiological data support the idea that there can be a close linkage between the system responsible for stimulus analysis and that responsible for the activation of responses. Thus, as evidence about a particular stimulus waxes *and wanes*, so activation of the associated responses will increase *and decrease*. According to this view, then, a decrease in response activation does **not** reflect the operation of an abortion process. Rather, it reflects the fact that evidence in favor of a particular response is declining. Second, in one experiment (Gratton et al., 1988: Figure 6), we found evidence for the mutual inhibition of two concurrently activated responses in two-choice reaction time experiments. As the activation of one response approached the threshold required for overt response execution, so the activation of the other response decreased. This kind of inhibitory coupling is similar to that observed for EMG and squeeze responses (see above) and presumably represents the operation of a local control process rather than a centrally initiated abortion process.

Thus, our data indicate that decrease in response activation can occur **without** there being an active inhibitory process (i.e., abortion) of the kind proposed by Kornblum and his colleagues. This is not to say that such an active process might not be operative. In fact, in a different experimental context, we did find evidence for an active inhibitory mechanism (De Jong, Coles, Logan, & Gratton, 1990). However, this mechanism appeared to function to inhibit **all** activated responses. Such a mechanism would clearly be inappropriate in the kind of two-choice reaction time experiments described earlier in which some response must **always** be executed.

## 3. CONCLUSIONS

### 3.1 The locus of the stimulus-response compatibility effect

Our psychophysiological data provide support for the existence of a generic response activation process that is an essential aspect of the explanation of stimulus-response compatibility effects proposed by Kornblum and his colleagues. Both peripheral and central measures suggest that, under some circumstances, responses are activated automatically following stimulus presentation.

These data were derived from two experimental paradigms. In one paradigm (Osman et al., in press), there was dimensional overlap between stimulus and responses sets (location) and the LRP measure revealed that a *relevant* stimulus attribute (location) was associated with response activation under incongruent mapping conditions. In the second paradigm (the Eriksen paradigm), an *irrelevant* stimulus attribute (peripheral noise letter identity) was also associated with response activation. In particular, when relevant (i.e., target letter identity) and irrelevant attributes conflicted, the incorrect response was activated.

In a recent paper, Hasbroucq and Guiard (1990) have argued that the effects of irrelevant S-R incongruity are best understood in terms of stimulus incongruity rather than in terms of S-R incongruity (see also Stoffels & van der Molen, 1988). Thus, delays in reaction time that are occasioned by a conflict between relevant and irrelevant stimulus attributes (as in the Eriksen paradigm) are ascribed to delays in stimulus processing rather than to delays due to the activation of an incorrect response. It is clear that our psychophysiological data are at variance with this ascription -- we have clearly demonstrated that incorrect response activation occurs in the Eriksen paradigm. However, our data also indicate that the delay in reaction time that can be attributed to incorrect response activation and response competition is not sufficient to account for the overall effect of noise-compatibility.

In the experiment by Coles et al. (1985), the effect of noise-compatibility on reaction time was 47 ms. Based on our analysis of the temporal dynamics of correct response execution as a function of incorrect response activation, we were able to determine that response competition effects could account for 22 ms of the noise-compatibility effect. Thus, 25 ms remained to be explained by other mechanisms. In this experiment, we also measured the P300 component of the event-related brain potential. We have argued elsewhere that the latency of this component reflects the duration of stimulus evaluation processes and is relatively independent of response-related processes<sup>5</sup> (Donchin & Coles, 1988). In fact, P300 latency was 27 ms longer when the noise was incompatible, suggesting that stimulus evaluation processes were prolonged by incompatibility. Thus, it appears that **both S-S incongruity and S-R incongruity** effects operate in the Eriksen paradigm to delay reaction time (see Coles et al., 1985, for details of these analyses).

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<sup>5</sup> This claim has been challenged by those who consider that the results of Ragot and his colleagues (Ragot, 1984; Ragot & Renault, 1981) demonstrate that P300 latency is sensitive to response-related processes. Ragot found that P300 latency was longer, when the (irrelevant) spatial position of a light did not correspond with the side of the response hand indicated by the light. In fact, when the data obtained in these experiments are analyzed in terms of the scheme proposed by Hasbroucq and Guiard (1990), the effect on P300 is attributable to S-S incongruity rather than to irrelevant S-R incongruity. Of course, the finding of an effect of S-S incongruity on P300 latency is entirely consistent with the proposal that this measure is sensitive to the duration of stimulus evaluation processes. Note also that in Ragot's work, **relevant** S-R incongruity was not associated with a delay in P300 although it did delay reaction time.

### 3.2 The Verification Process

Our data support the proposal of Kornblum and his colleagues that "automatically" activated responses are checked against the required response. The presence of a distinctive brain potential component on incorrect trials suggests that a special process is invoked when there is a mismatch between activated and required responses. However, it is presently unclear whether this brain potential component is a manifestation of error detection or whether it is more closely related to the consequences of error detection, among which may be an attempt to abort the incorrect response. There are, of course, other functions that are served by a response verification process. For example, Rabbitt has shown that the detection of an error on a particular trial leads to a change in behavior on subsequent trials (Rabbitt, 1966; see also Donchin, Gratton, Dupree, & Coles, 1988). Thus, an error-detection mechanism is clearly an important component of any model of human information processing, although its *raison d'être* need not be inextricably linked to an abortion process.

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