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Probability Effects on Stimulus Evaluation and Response Processes

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This study investigated the effects of probability information on response preparation and stimulus evaluation. Eight subjects responded with one hand to the target letter *H* and with the other to the target letter *S*. The target letter was surrounded by noise letters that were either the same as or different from the target letter. In 2 conditions, the targets were preceded by a warning stimulus unrelated to the target letter. In 2 other conditions, a warning letter predicted that the same letter or the opposite letter would appear as the imperative stimulus with .80 probability. Correct reaction times were faster and error rates were lower when imperative stimuli confirmed the predictions of the warning stimulus. Probability information affected (a) the preparation of motor responses during the foreperiod, (b) the development of expectancies for a particular target letter, and (c) a process sensitive to the identities of letter stimuli but not to their locations.

People respond quickly to likely events. This assertion is based on the analysis of response speeds measured in choice reaction time (RT) tasks, in which subjects must choose the response appropriate to a particular stimulus (the imperative stimulus) from a set of several alternative responses. Beginning with Hick (1952) and Hyman (1953), many investigators have found that RT after a stimulus is presented decreases as subjects are given more information regarding the likelihood of the stimulus–response pair. Explanations of this phenomenon commonly invoke the concepts of preparation and priming (for a review, see Requin, Brener, & Ring, 1991); that is, the information that the subject possesses somehow changes processing to allow faster performance. The preparation might accomplish in advance the operations that the system would otherwise carry out after the imperative stimulus appears, or it might preset the usual processing operations, thereby improving their efficiency (Requin, 1985).

Precisely which elements of the information-processing system are changed by the preparatory activity—where in the system preparation is implemented—remains a matter of some controversy. One may characterize the effects of preparation according to their loci in the information-processing system. In the case of probability information, a basic question is whether the information affects processing of the stimulus, emission of the response, or some combination of the two. This distinction between sensorial and motor preparation had an important role in the early history of experimental psychology (Woodworth, 1938), and the aim of our study is to contribute to a resolution of the issue. We studied the effect that prior information about probability of events has on both perceptual preparation and motor preparation. The unique aspect of this study is that we used event-related brain potentials (ERPs) to monitor the consequences of preparation in different loci, thus augmenting the tools normally available in the study of preparation.

Several research strategies have evolved to determine the locus or loci of probability effects. These strategies can be categorized into two broad classes of paradigms, distinguishable by how an investigator may relate observable phenomena to the theoretical constructs that constitute a model of the information processing system: (a) manipulating independent variables that affect particular subsystems and (b) measuring dependent variables that manifest the activity of particular subsystems. We argue that experiments incorporating the second approach have the potential to provide richer insights into the mechanisms of preparation.

The Selective Influence of Independent Variables

Using the first approach, investigators have manipulated independent variables that were thought to affect particular elements of the information processing system and have measured the effects that such manipulations had on a dependent variable such as RT or accuracy (e.g., Donders, 1868/1969; Sternberg, 1969). In this way, it was possible to attribute changes in the dependent variable to changes in the information processing component that had been manipulated.

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However, as we argue, it is difficult to use the independent variable approach to determine the separate contributions of multiple processing components when only one variable has been manipulated. In the context of research on preparation, in which effects of both sensory and motor preparation are possible, this approach cannot be used to identify the loci of preparatory effects without multiple experimental manipulations. The number of loci that can be identified is limited by the number of conditions that are compared.

A Priori Probability Studies

Investigators have used at least three experimental paradigms to try to dissociate the roles of perceptual and motor preparation in choice RT tasks. The first class of studies, which builds most directly upon the work of Hick (1952) and Hyman (1953), varies the a priori probability of stimulus–response pairs. In order to manipulate certain elements of the information-processing system selectively, more than one stimulus is associated with a particular response. For example, LaBerge and Tweedy (1964) found that manipulating the probability of two stimuli associated with the same response resulted in faster RTs for the more probable stimulus; this finding supported the notion that one locus of probability effects might be in stimulus-related processing. To isolate the effects of response processes, Biederman and Zachary (1970) varied the probability of the response associated with a stimulus by manipulating the probability of other stimuli associated with that response. In that experiment, stimulus probability exerted a strong influence on RT and error rate. Response probability effects were smaller and mostly confined to error rate. Miller and Pachella (1973), who used additive factors logic (Sternberg, 1969), reported that stimulus probability interacted with stimulus contrast, which suggests that at least one locus of the stimulus probability effect is in stimulus encoding. Others (e.g., Hawkins, MacKay, Holley, Friedin, & Cohen, 1973) found that stimulus–response compatibility interacted with stimulus probability, which suggests that probability can exert its effect at the response-selection locus.

Although these results indicate that stimulus probability affects both stimulus- and response-processing loci, one must view the results with caution. In some studies (e.g., LaBerge & Tweedy, 1964), researchers have manipulated one independent variable while holding the others constant, thus limiting the analysis to the one possible locus. In other studies (e.g., Biederman & Zachary, 1970) researchers have assessed the relative contributions of both a stimulus-processing locus and a response-processing locus to the probability effect, but these researchers have compared the effects in separate experimental manipulations. Such an approach assumes, of course, that the manipulations do not affect the nature and the quality of all other aspects of information processing, an assumption that has proved problematic since Kulpe's (1893/1909) critique of Donders's (1868/1969) subtraction logic.

Conditional Probability Studies

An alternative strategy is to use a precue, or a priming stimulus, to vary the probability distribution of the imperative stimuli from trial to trial. In this paradigm, an informative precue precedes the imperative stimulus and indicates to the subject the probability that a particular imperative stimulus will appear during that trial. The effects of this kind of precue are evident in performance benefits when predictions about the imperative stimulus are confirmed and in performance costs when such predictions are disconfirmed (Posner, 1978).

In studies that vary conditional probability researchers often confine their attention to only one possible processing locus. For example, some investigators have examined the effects of a precue on response-related processing (e.g., Meyer, Yantis, Osman, & Smith, 1984, 1985; Miller, 1982; Rosenbaum, 1980), whereas others have concentrated on the effects of a precue on the processing of the imperative stimulus (e.g., Neely, 1977; Posner & Snyder, 1975). In both kinds of studies, the precue has resulted in costs and benefits to performance. Accordingly, explanations for the effect of the precue have invoked various types of response preparation mechanisms (see Meyer et al., 1984, 1985), perceptual biases (e.g., Bertelson, 1967), early activational and late attentional mechanisms (Neely, 1977; Posner & Snyder, 1975), and perceptual coding mechanisms (Posner, 1978).

The approach exemplified in the studies just reviewed has been relatively successful in identifying the locus of preparatory effects when the precue is believed to influence only one process. However, the approach is more difficult to apply to situations in which the precue may influence several of these processes. For example, one circumstance in which both types of loci (perceptual and response) may be important is in experimental paradigms in which the stimulus that serves as the warning stimulus is included among the possible imperative stimuli. On some trials the imperative stimulus is identical to (i.e., matches) the warning stimulus, and on other trials the warning stimulus and the imperative stimulus mismatch. It has been shown that when the imperative stimulus matches the warning stimulus, the RT is reduced in comparison with the RT for an imperative stimulus mismatch of the same probability, even if that probability is rather low (Duncan-Johnson & Donchin, 1982; Posner & Snyder, 1975).

Studies that have used precues which did not provide response information (e.g., Posner & Snyder, 1975) attributed the effect to a facilitation in the processing of the matching imperative stimulus. Nonetheless, in situations in which the warning stimulus offers response information as well as stimulus information, it is possible that this effect of matching on the RT is not an exclusively perceptual effect. Duncan-Johnson and Donchin (1982), for example, examined the effects of informative warning stimuli on RT and found that the advantage of a confirmation and the disadvantage of a disconfirmation were greater when the warning predicted the same letter (i.e., a match) than when it predicted a different letter (mismatch). Duncan-Johnson and Donchin suggested that subjects prepare the response to a lesser extent when the warning stimulus predicted a mismatch.

Subjective Probability Studies

A third type of design does not manipulate the objective probability of the imperative stimulus but relies instead on fluctuations in subjective probability. Subjects respond faster to a stimulus when it is preceded by a trial in which an identical stimulus occurred (and an identical response was required) than when preceded by a different type of trial (Bertelson, 1961, 1963). These sequential effects may extend over several trials (Remington, 1969). In studies of a priori and conditional probability, preparation is rational, given the probability distribution of imperative stimuli. In studies of subjective probability, however, the information processing system prepares for a particular stimulus even when this preparation is unrelated to the actual probability distribution of imperative stimuli. It is not clear whether the subject consciously holds the expectancies in subjective probability studies. Indeed, evidence indicates that a combination of passive, automatic priming and more active expectancies may have a role in such preparation (Soetens, Boer, & Hueting, 1985; see also Karis, Chesney, & Donchin, 1983).

In one series of studies, researchers have attempted to determine whether the sequential effects are attributable to the priming of stimulus evaluation processes, the preparation of response processes, or some combination of the two (e.g., Bertelson, 1965; Rabbitt & Vyas, 1973). For example, Rabbitt and Vyas (1973), using evidence from their own and others' work, suggested that these sequential effects may have at least five loci within the information-processing system. Like the manipulations of a priori and conditional probability, this work on subjective probability typically focuses on particular processing loci by manipulating the type of stimulus or response repetitions. Thus the weakness that limits the studies of a priori and conditional probability also limits these studies: The number and choice of experimental manipulations constrains the number and type of processing loci that researchers may identify.

In summary, the evidence based on the manipulation of independent variables suggests that perceptual preparation and response preparation may be active in different experimental conditions. This approach, however, is limited in that no more than one processing locus can be examined when only a single independent variable is manipulated. When multiple independent variables are manipulated, the number of processing loci that can be identified increases, but only as a function of the number of manipulations. Furthermore, which processing loci researchers identify depends on which variables they manipulate. In the following section, we present a way to augment the independent variable approach that overcomes some of these limitations.

The Selective Sensitivity of Dependent Variables

Another way to investigate the locus or loci of probability effects is to measure dependent variables that manifest the activity of particular information-processing subsystems. Such measures allow one to study the behavior of each subsystem in isolation from other systems. In the context of this article, we were able to use these selectively sensitive measures to determine the effect of an informative precue on specific information processing subsystems. Of course, the utility of this approach is entirely dependent on the nature and the validity of the mapping between the dependent variables and the information-processing subsystems, such as perceptual processing and response activation. (For a discussion of these issues, see Cacioppo & Tassinary, 1990; Coles, 1989; Coles, Gratton, & Gehring, 1987; Donchin, 1979; Donchin & Coles, 1988.) We used components of ERPs in this way, and in subsequent sections, we describe the inferential logic underlying this use of ERPs and consider the evidence that justifies the use of three particular ERP components.[1]

Event-Related Brain Potentials and Preparation

Two key assumptions were involved in our use of ERP components as tools in the study of cognition (cf. Donchin & Coles, 1988): (a) An ERP component manifests the operation of some subsystem of the information-processing system, and (b) changes in the amplitude of an ERP component manifest changes in the degree of activity of that subsystem, whereas changes in the latency of the component reflect the duration of all the processes that must precede the activation of the manifested subsystem. The word *manifestation* is used in this context to indicate that the measures of electrical activity recorded at the scalp may have an indirect relation to the actual neural processes responsible for their generation. The virtue of these voltages, however, is that they allow one to "visualize"—that is, they *manifest*—the activity of some intracranial subsystem. This much is not an assumption. What is an assumption is that one can interpret the consistency with which a particular component is elicited in terms of its relation to the imposition of specific information-processing demands on the system. The mapping between an ERP component and the activity of a subsystem is established through an examination of the antecedent conditions that control the amplitude and the latency of the components (Donchin, 1981; Donchin & Coles, 1988).

In this article, we report a study in which we capitalized on three mappings between ERP components and processes that are associated with preparation. In particular, we evaluated the development of response preparation, using ERPs measured during the foreperiod of a warned RT task, and identified the presence of two kinds of perceptual preparation by examining ERP responses to the imperative stimulus. In the following paragraphs, we justify the use of the different ERP components to monitor the behavior of different information-processing subsystems in the context of our experimental paradigm.

Response preparation. One can estimate the extent to which response preparation processes have been activated by deriving the difference between the amplitudes of the readiness potential (RP) measured over the right and left cerebral hemispheres (Coles, 1989). The RP is a negative-going potential that emerges some time before a movement is executed, and it rises gradually to a peak just before the movement (Kornhuber & Deecke, 1965; Kutas & Donchin, 1974, 1980; Rohrbaugh, Syndulko, & Lindsley, 1976; Vaughan, Costa, &

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[1] As is customary, we define components of the ERP in terms of their latency, polarity, and scalp distribution, as well as their sensitivity to experimental manipulations (see Donchin, Ritter, & McCallum, 1978).

Ritter, 1968). There is a clear relation between the amplitude distribution of the RP over the scalp and the somatotopic distribution of motor control along the central sulcus. Vaughan et al. (1968) studied RPs preceding movements ranging from the head to the feet and found that the point of maximal amplitude of the RP on the scalp corresponds to the known locus of movement control centers in the underlying neural tissue. In accordance with the known lateralization of the motor system, Kutas and Donchin (1974, 1980) reported that the RP that precedes finger and hand movements is larger at scalp sites contralateral to the hand executing the movement. Furthermore, Kutas and Donchin (1980) and Rohrbaugh et al. (1976) reported that this asymmetry of the RP can develop before the imperative stimulus in RT tasks as well as before voluntary self-paced movements. Kutas and Donchin (1980) proposed that as a result, the RP asymmetry can be used as an index of movement-related preparation. Magnetoencephalographic evidence relating the RP to motor cortex activity (Okada, Williamson, & Kaufman, 1982) lends credence to this suggestion.

Not all asymmetries between the right and left RPs can be attributed to motor preparation. Thus if one is to use the difference in electrical activity between left- and right-hemisphere electrode sites as an index of movement-related preparation, it is important to eliminate from the recordings those asymmetries that are not related to movement preparation. Fortunately, many choice RT studies are not concerned with preparation of the left- or right-hand response per se but rather are concerned with preparation of a response that may, on different trials, be associated with either hand. Thus the subject may be instructed to respond to a target with the right hand on some trials and with the left hand on others. Such an arrangement allowed us to examine the preparation of responses to targets independent of the specific hand with which the response is executed. Preparation to respond in this manner can be computed as the difference between the RP amplitude at the scalp site contralateral to the side of the response of interest (e.g., the correct response) and the RP amplitude ipsilateral to that side. By averaging trials in which the response of interest occurs in the left hand with trials in which that response occurs in the right hand, the nonmotoric asymmetries are eliminated (see Coles, 1989, for a description of this procedure). We refer to this measure as the *lateralized* readiness potential (LRP).

Several investigators have used the LRP to indicate the direction and the degree of motor preparation (see Coles, 1989; Coles & Gratton, 1986; de Jong, Coles, Gratton, & Logan, 1990; de Jong, Wierda, Mulder, & Mulder, 1988; Gratton, Coles, Sirevaag, Eriksen, & Donchin, 1988; Osman, Bashore, Coles, Donchin, & Meyer, 1988; Smid, Mulder, & Mulder, 1990). We used the measure to determine the extent to which the delivery of information about the probability of subsequent responses triggers preparatory processes in the motor system before the imperative stimulus appears. Furthermore, we could evaluate the consequences of motor preparation for the speed and accuracy of the overt behavioral response after presentation of the imperative stimulus (cf. Gratton et al., 1988).

Perceptual preparation. Two ERP components appear to manifest processes that are invoked during stimulus processing and are affected by probability information. A variety of experiments have shown that the N200, a negative component characterized by a centrally maximal scalp distribution, is elicited by improbable stimuli (for reviews, see Näätänen & Picton, 1986; Pritchard, Shappell, & Brandt, in press). The relevance of the N200 to the study of probability effects is evident in the data of Duncan-Johnson and Donchin (1982), in which a large N200 was elicited by stimuli that were improbable according to the preceding warning stimulus. The N200 thus appears to manifest a stimulus evaluation process that is sensitive to probability information.[2]

Another component that is sensitive to probability information is the P300, a positive component characterized by a parietally maximal scalp distribution. Substantial literature indicates that the amplitude of the P300 component of the ERP is determined in part by the subjective probability and the task relevance of the eliciting stimulus (for reviews, see Donchin, 1981; Donchin & Coles, 1988; Johnson, 1988). Furthermore, Duncan-Johnson and Donchin (1982) found that the P300 was larger in response to stimuli that disconfirmed warning stimulus predictions. Although the N200 and P300 components are often sensitive to the same experimental manipulations, the temporal relation between the two components (the N200 occurs before the P300) suggests that the two components may manifest different kinds of probability-sensitive processes. In particular, the N200 may depend on more elementary attributes of the predicted and actual stimuli (e.g., their physical features) than does the P300.

As stated earlier, one aim of our study was to determine whether prior information about the probability of events leads to a presetting or to some other preparatory activity in perceptual systems. The distinction between the N200 and the P300 may allow one to determine not only whether probability information affects the perceptual system but, more precisely, which elements of the perceptual system are prepared.

In our study, subjects had to respond as a function of the identity of a target letter presented in noise (other letters). On half the trials, the noise letters called for the same response as the target letter; in the other trials, the noise letters called for a different response. Interpreting their data in light of Treisman and Gelade's (1980) feature-integration theory of attention, Gratton et al. (1988) suggested that in this kind of task, there are at least two phases in stimulus evaluation: in the early phase, the system determines the identities of both target and noise letters, regardless of their locations; in a later phase, information about the letter locations is derived. Probability information may affect early processes involved in encoding the identities of the letters, or later processes that have access to the information about the identity of a letter at a designated

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[2] Others (Näätänen & Picton, 1986; Pritchard, Shappell, & Brandt, in press) have referred to the N200 component of which we speak as the "N2b," distinguishing it from the mismatch negativity (Näätänen & Picton, 1986), or "N2a" (Pritchard et al., in press), which occurs when the physical features of a stimulus mismatch those of immediately antecedent stimuli (see also Breton, Ritter, Simson, & Vaughan, 1988, for an examination of this issue). For ease of exposition, we refer to the component as the N200, recognizing that it is a centrally maximal component sensitive to violations of stimulus expectancy.

(target) location, or both. Our experiment incorporated manipulations that may have enabled us to dissociate preparation that the information-processing system has implemented for particular stimulus features from the preparation for particular features when they are in designated locations. In this context, the N200 should be sensitive to more primitive kinds of deviance (i.e., unexpected stimulus features), whereas the P300 should be sensitive to more global kinds of expectancy violations.

THE PRESENT EXPERIMENT

To summarize, the aim of our experiment was to examine preparatory processes in a warned, choice RT paradigm. The task that we chose was adapted from Eriksen and Eriksen's (1974) study and has been used in several studies in our laboratory (Coles, Gratton, Bashore, Eriksen, & Donchin, 1985; Gratton et al., 1988). Subjects were required to make a speeded left- or right-hand response as a function of the central letter of a five-letter array. Surrounding the central letter were noise letters that corresponded either to the correct response (*HHHHH* or *SSSSS*) or to the incorrect response (*SSHSS* or *HHSHH*). The paradigm consisted of four blocks of trials. In the first two blocks, the warning provided no information about the nature of the imperative stimulus. In one block, the warning was the asterisk symbol, and in another block the warning was the letter *H* or *S*. In the other two blocks, a warning letter predicted the central letter of the subsequent array with a probability of .80: in one block, it predicted the matching response letter (e.g., *H* predicts *H*), and in the other, it predicted the mismatching response letter (e.g., *H* predicts *S*).

We employed psychophysiological measures and measures of overt behavior to address several issues regarding preparatory processes in the context of this paradigm. We used measures of the LRP to investigate the role of motor preparation and measures of the N200 and P300 to study the generation of stimulus expectancies.

Method

Subjects

Eight University of Illinois students (2 women and 6 men) between the ages of 18 and 30 served as subjects. They were paid $3.50 per hour plus bonuses for participation. All were right-handed and had normal or corrected-to-normal vision. One male subject made anticipatory responses on more than 60% of the trials in two of the experimental conditions (80/20 and 20/80, to be described). The data from this subject were excluded from further analysis and were replaced by those of a ninth subject (female), who was tested under exactly the same experimental conditions.

Stimuli

Stimuli were presented on a Hewlett-Packard cathode ray tube display (No. 1310A). Subjects sat 1 m from the screen, so that the visual angle subtended by each letter was approximately 0.5°; the visual angle subtended by the entire array was about 2.5°. A fixation point, visible throughout the experiment, was placed 0.1° below the location of the target letter. The onsets of warning and imperative stimuli (duration = 100 ms) were separated by 1,000 ms. Subjects were allowed 1,000 ms after the onset of imperative stimulus to respond. The interval between the onsets of two consecutive trials was 2,500 ms.

Procedure

The task was to make a speeded discriminative response as a function of the central target letter in a five-letter stimulus array. Subjects were instructed to respond with one hand to the target letter *H* and with the other to the target letter S by squeezing one of two zero-displacement dynamometers. Surrounding the target letter were compatible or incompatible noise letters. As a result, four target arrays were possible: *HHHHH, SSHSS, SSSSS,* and *HHSHH.*

Each subject was tested in four conditions. In each condition, a warning stimulus was presented 1,000 ms before each target array. The four conditions differed, however, according to the predictive value of the warning stimulus. In the first two conditions, the warning stimulus offered no information about the central letter of the subsequent array. In one of these conditions (the Star condition), the asterisk symbol was the warning stimulus. In the other (50/50) condition, an *H* or an *S* preceded the target, but this warning letter did not predict which letter would appear as the target. The warning letter had predictive value in the other two conditions: In the 80/20 condition, the warning letter was the same as the target letter on 80% of the trials; in the 20/80 condition, the warning letter was the opposite of the target letter on 80% of the trials.

Each subject took part in four sessions, one on each of 4 separate days. Each session corresponded to one of the four conditions and consisted of 22 blocks of 80 trials per block. The first two trial blocks were devoted to practice. The two neutral conditions (Star and 50/50) were presented first, and their order was counterbalanced across subjects, as was the order of presentation of the subsequent predictive conditions. Hand of response (left = *H*/right = *S* or left = *S*/right = *H*) was also counterbalanced across subjects. Subjects were instructed to respond "as quickly as possible, while remaining reasonably accurate."

Overt Responses

The subjects responded to the target letter by squeezing one of two zero-displacement dynamometers (Daytronic Linear Velocity Force Transducers, Model 152A, with Conditioner Amplifiers, Model 830A; see Kutas & Donchin, 1977). A transducer transformed the force applied to the dynamometer into a voltage. This voltage was digitized at 100 Hz for 1,000 ms after array presentation. For each subject, 25% of his or her maximal squeeze force was determined before the first session. A circuit determined when the output of the transducer exceeded this criterion value, defining the occurrence of an overt response and its corresponding reaction time. During practice trials, an auditory click was presented to the subjects over a loudspeaker whenever the squeeze force crossed the criterion.

Psychophysiological Recording

The electroencephalogram (EEG) was recorded from Fz, Cz, Pz, C3′ (4 cm to the left of Cz), and C4′ (4 cm to the right of Cz), according to the 10/20 International System (Jasper, 1958). Electrooculographic activity (EOG) was recorded from electrodes affixed with adhesive collars above and below the right eye and at 2 cm external to the outer canthus of each eye. A ground electrode was placed on the forehead. The electrodes were referenced to linked mastoids. The electromyogram (EMG) was recorded from electrodes at standard forearm flexor placements (Lippold, 1967) on each arm.

All electrodes were Beckman biopotential Ag/AgCl electrodes affixed with Grass EC2 electrode cream. Impedance for EEG and EOG electrodes was below 10 kohm; EMG electrode impedance was less than 20 kohm.

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

In each case, the derived Voltage × Time functions were digitized at 100 Hz for 2,100 ms, starting 100 ms before the presentation of each warning stimulus.

Data Reduction

Overt Responses

As noted earlier, the subjects were required to squeeze the dynamometers to a criterion of at least 25% of maximal 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 the accuracy and the latency of overt responses on every trial.

Although this squeeze criterion was used for feedback to the subjects, we used a measure of the onset latency of the EMG response for all analyses to be reported. We chose to use this measure, rather than a measure based on squeeze activity, because EMG is a more sensitive measure of the activation of overt responses. (As we show later, the EMG and squeeze data were, in fact, very similar.) To determine the moment of onset, we established the minimal value of the integrated EMG activity that was discriminable from noise (baseline). This procedure consisted of examining the distribution of maximal single-trial EMG amplitudes for each subject, for each side separately. This distribution had a pronounced bimodal shape as a result of the contribution of trials in which an EMG response had occurred and trials on which an EMG response had not occurred. A value was chosen to discriminate maximally between the two parts of the distribution. This value became the criterion for overt response initiation; the point at which this criterion was crossed defined the latency of EMG onset.

The accuracy of trials was determined according to the first EMG response that occurred during a trial. For example, trials were classified as error trials when the first EMG response exceeding the noise baseline criterion occurred on the incorrect side. This procedure classified as error trials some trials on which a subsequent, correct EMG response occurred. Trials on which no response was detectable, trials on which correct and incorrect responses occurred simultaneously, and trials on which responses occurred within 50 ms of the target stimulus were eliminated from all analyses.

Event-Related Potential Data

The EEG data for each single trial were corrected for the ocular movement artifact through a procedure described by Gratton, Coles, and Donchin (1983).

To compute P300 and N200 latency and amplitude measures, we combined the waveforms from the five scalp electrodes to obtain a composite waveform for each component by differentially weighting the values obtained at the five scalp electrodes (vector filter; Gratton, Coles, & Donchin, 1989). The weights were derived on the basis of previous research (see Gratton, Kramer, Coles, & Donchin, 1989, and our Results section) and were selected to optimize the discrimination between P300, N200, and other sources of electrical activity in the brain.[3] A baseline consisting of the 100 ms preceding the imperative stimulus was subtracted from each waveform. For P300 measures, the waveforms were then smoothed by means of a low-pass digital filter (the high-frequency cut-off point was 6.29 Hz). The peak of the P300 was identified as the maximal value of the vector filter output within a 300- to 700-ms window after the stimulus. This value was recorded as the amplitude, and the latency of this maximum was taken as the latency of the P300. This procedure has proved to be both reliable and valid (Fabiani, Gratton, Karis, & Donchin, 1987; Gratton, Kramer, et al., 1989). For N200 amplitude measures, the average amplitude in specified windows was computed (see Results section). To obtain a sufficient number of trials in each averaging bin, we pooled across all trials, regardless of accuracy, to derive the N200 and P300 measures.

We estimated the amplitude of the LRP on each single trial at each electrode by computing the average C3′ and C4′ values over the 100 ms that preceded the appearance of the imperative stimulus. We derived a measure of the LRP that indexed how much the subject prepared to respond to a stimulus that matched the warning letter; that is, if *H* was the warning letter, this LRP measure indexed how much the subject prepared the *H* response. To compute the amount of lateralization on each trial, we first determined which hand would be the correct one to use if the warning letter appeared as the target stimulus. We subtracted the value at the electrode site ipsilateral to that hand from the value at the site contralateral to that hand. Thus if *H* was the warning letter and *H* was assigned to the right hand, the LRP value for that trial would have been C3′ − C4′. (For the Star condition, this determination was made randomly.) Because the readiness potential itself is negative, this procedure yielded a measure for which negative values indicate that the subject prepared to respond to a target letter that matched the warning letter; positive values suggest preparation of the opposite-letter response. This procedure eliminated asymmetries not associated with movement and yielded a waveform that was equivalent to the "corrected motor asymmetry" described by de Jong et al. (1988; see also Coles, 1989).

Results

We begin by examining the effects of the various experimental manipulations on reaction time and accuracy. Using the psychophysiological data, we then review the nature of the preparatory mechanisms underlying the facilitation of response speed by the warning stimuli. We next examine evidence that prior information is used to prepare the motor system. Finally, we show that perceptual analysis mechanisms are primed by the information carried by the warning stimulus. We use the following terms:

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[3] One issue in the analysis of ERPs concerns the fact that several overlapping ERP components may contribute to the waveform observed at the scalp. Vector filtering is a method for disambiguating the observed waveform into the components that contribute to it. First it is assumed that different components have different (and specifiable) scalp distributions, and then the method provides an estimate of the degree to which each component is present at each time point in the waveform. The method contains no assumptions about the time course of the underlying components (see Gratton, Coles, & Donchin, 1989).

1. *Match* trials were those in which the warning and the imperative stimuli consisted of the same letter. (After an *H* as a warning stimulus, the imperative stimuli would be either *HHHHH* or *SSHSS*. "Matching" refers only to the relation of the warning letter to the central character.)
2. *Mismatch* trials were those in which the warning and the imperative stimuli were different letters.[4]
3. *Compatible noise* consisted of surrounding noise letters that were the same as the target letter (i.e., *HHHHH* and *SSSSS*).
4. *Incompatible noise* consisted of noise letters that were different from the target letter (i.e., *HHSHH* and *SSHSS*).
5. *Confirmation* was the situation in which the more likely target—that is, the one whose probability was indicated to be .80—occurred during the trial.
6. *Disconfirmation* was the situation in which the unlikely ($p = .20$) imperative stimulus occurred during the trial.

Analysis of Overt Responses[5]

Effects of the Probability Manipulation

This study was designed to assess how subjects prepare when they are given prior information about event probabilities. It was therefore critical to assess the degree to which informative warning stimuli served their purpose. For this reason, we examined the RTs and the error rates as a function of the information delivered by the warning stimulus. If the subject prepared for the probable stimulus, the response to it should be faster and more accurate.

Reaction time. The RTs obtained on correct response trials were submitted to a 4 × 2 × 2 (Predictive Condition × Compatibility × Match/Mismatch) repeated-measures analysis of variance (ANOVA). A main effect of predictive condition was found to be statistically significant, $F(1.54, 10.77) = 7.35$, $p < .025$, $MS_e = 7{,}237.88$. Planned comparisons revealed that correct RTs in the 80/20 and 20/80 conditions were faster than correct RTs in the Star and 50/50 conditions, $F(1, 7) = 9.53$, $p < .025$, $MS_e = 16{,}131.32$. This pattern of results is seen in Figure 1.[6]

As expected, responses in the 80/20 and 20/80 conditions were faster on confirmation trials than on disconfirmation trials. The Predictive Condition × Match/Mismatch interaction supported this observation, $F(1.73, 12.12) = 93.73$, $p < .001$, $MS_e = 658.16$. As Figure 1 suggests, correct responses were faster on match trials than on mismatch trials in the 80/20 condition, $F(1, 7) = 98.52$, $p < .001$, $MS_e = 1{,}393.50$, and faster in mismatch trials than in match trials in the 20/80 condition, $F(1, 7) = 62.38$, $p < .001$, $MS_e = 831.07$. Responses on match and mismatch trials did not differ in the Star condition, $F(1, 7) = 0.71$, $p > .05$, $MS_e = 44.93$, or the 50/50 condition, $F(1, 7) = 2.71$, $p > .05$, $MS_e = 99.71$.

Finally, Figure 1 suggests that the flanking characters exercised a different effect on the correct RTs in the four predictive conditions. The predictive condition interacted with the compatibility of the noise, $F(2.10, 14.67) = 4.87$, $p < .025$, $MS_e = 209.09$. Planned comparisons indicated that responses on compatible trials were faster than responses on incompatible trials in the Star condition, $F(1, 7) = 14.41$, $p < .01$, $MS_e = 371.77$, and the 50/50 condition, $F(1, 7) = 12.00$, $p < .025$, $MS_e = 350.89$, but not in the 80/20 condition, $F(1, 7) = 0.08$, $p > .05$, $MS_e = 952.20$, or the 20/80 condition, $F(1, 7) = 0.59$, $p > .05$, $MS_e = 718.57$.[7]

Conditional accuracy functions. We observed further details concerning the effects of the different manipulations on the speed of the subjects' responses by examining the accuracy achieved by the subjects at different speed levels (cf. Ollman, 1977).

For each subject, the RTs were categorized into four bins according to the quartiles of the RT distribution obtained for the subject across all four predictive conditions. Accuracy was computed as proportion correct and was transformed for the purposes of the ANOVA through the arcsine transformation (Neter, Wasserman, & Kutner, 1985). These measures were then submitted to 4 × 2 × 2 × 4 (Predictive Condition × Match/Mismatch × Noise Compatibility × RT Bin) repeated-measures ANOVA. The cell means from the analysis are presented in Figure 2 as proportion correct.

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[4] For the purpose of the analysis, the trials obtained in the Star condition, in which the terms *match* and *mismatch* have no relevance, were sorted randomly into the match and mismatch categories to maintain consistency with the subtraction of C3′ from C4′ explained earlier.

[5] To correct for possible violations of the analysis of variance assumption of sphericity, the Greenhouse-Geisser correction to the degrees of freedom was applied to assess main and interaction effects (see Vasey & Thayer, 1987). The Greenhouse-Geisser degrees of freedom are those listed in the text. To perform multiple comparisons, we constructed contrasts, using separate error terms for each contrast and applying the Bonferroni correction in the case of nonorthogonal contrasts (see Maxwell, 1980).

[6] Corresponding accuracy values (proportion correct) are shown in Figure 2. We have chosen to consider accuracy data in the context of conditional accuracy functions (see the following discussion).

[7] We arranged the conditions so that the informative (80/20 and 20/80) conditions always followed the neutral (Star and 50/50) conditions in order that the precues in the neutral conditions were as neutral as possible—that is, had never been informative to the subject. Thus it was necessary to establish that the lack of a noise compatibility effect in the 80/20 and 20/80 conditions was not an effect of practice. Mean RTs were calculated separately for each set of two consecutive blocks of 80 trials each. This procedure yielded 20 mean values for the two neutral precue conditions and 20 for the two subsequent informative precue conditions. These values were submitted to a 2 × 2 × 20 (Compatibility × Neutral vs. Informative Precue Conditions × Block) repeated-measures ANOVA. A significant Compatibility × Precue Condition interaction was obtained, $F(1, 7) = 29.37$, $p < .001$, $MS_e = 529.52$, and the planned comparison again indicated that the effect of noise compatibility was greater in the neutral precue conditions than in the informative precue conditions. However, the size of the compatibility effect remained relatively constant throughout the first half of the experiment. In support of this observation, the Compatibility × Precue Condition × Block interaction was not statistically significant, $F(3.64, 25.47) = 1.37$, $p > .05$, $MS_e = 341.01$, which suggests that the size of the compatibility effect did not change with practice in either the neutral or the informative precue conditions of the experiment. This result confirms that the difference in the sizes of the compatibility effect in the neutral and informative precue conditions is not attributable to different levels of practice.

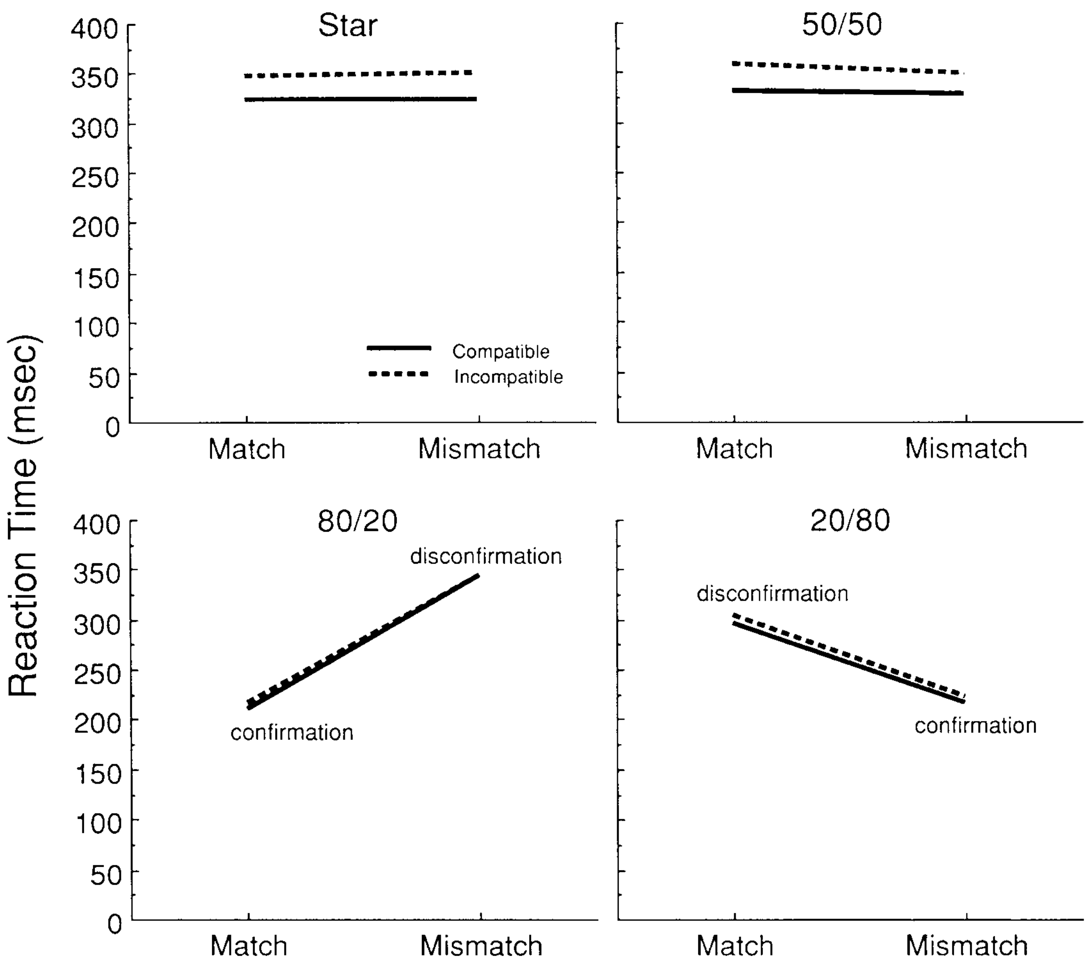

Figure 1. Mean electromyographic onset latencies (correct trials only) as a function of the experimental conditions (msec = milliseconds).

Figure 2 suggests that the effects of the match or mismatch between the warning and the imperative stimuli changed as a function of response speed and that this pattern was different in the STAR and 50/50 conditions from what it was in the 80/20 and 20/80 conditions. In particular, in the informative precue conditions, fast responses reflected a bias toward the precued response, whereas in the uninformative conditions, no such bias was evident. This impression was confirmed by a significant Predictive Condition × Match/Mismatch × RT Bin interaction, $F(3.22, 22.51) = 54.91$, $p < .001$, $MS_e = 0.098$. Planned comparisons clarified this scenario: for trials on which the warning stimulus provided no information and the responses were fast (the first RT bin in the Star and 50/50 conditions), subjects were as inaccurate on match trials as they were on mismatch trials, $F(1, 7) = 0.00$, $p > .05$, $MS_e = 0.041$, for the Star condition and $F(1, 7) = 1.82$, $p > .05$, $MS_e = 0.27$, for the 50/50 condition. In contrast, during the 80/20 condition, the accuracy was greater on match trials (confirmation trials) than on mismatch trials in the first RT bin, $F(1, 7) = 236.24$, $p < .001$, $MS_e = 0.19$. This effect was reversed in the 20/80 condition: accuracy was greater on mismatch trials (confirmation trials) than on match trials, $F(1, 7) = 160.17$, $p < .001$, $MS_e = 0.18$. When subjects responded more slowly in the 80/20 and 20/80 conditions, as shown by the data in the fourth RT bin, the difference in accuracy between match and mismatch trials was not significant: in the 80/20 condition, $F(1, 7) = 3.11$, $p > .05$, $MS_e = 0.19$; in the 20/80 condition, $F(1, 7) = 0.09$, $p > .05$, $MS_e = 0.16$.

Finally, subjects made more errors in responding to incompatible than to compatible noise arrays, $F(1, 7) = 73.42$, $p < .001$, $MS_e = 0.15$. This effect did not interact with the predictive condition manipulation.

These data confirm that the subjects understood and used the information provided by the warning stimulus with regard to the probabilities of particular imperative stimuli. It remains to be seen whether their use of this information was mediated by perceptual priming, by motor priming, or by both. Before turning to the psychophysiological data, however, we further examined the RTs and the error rates to determine the extent

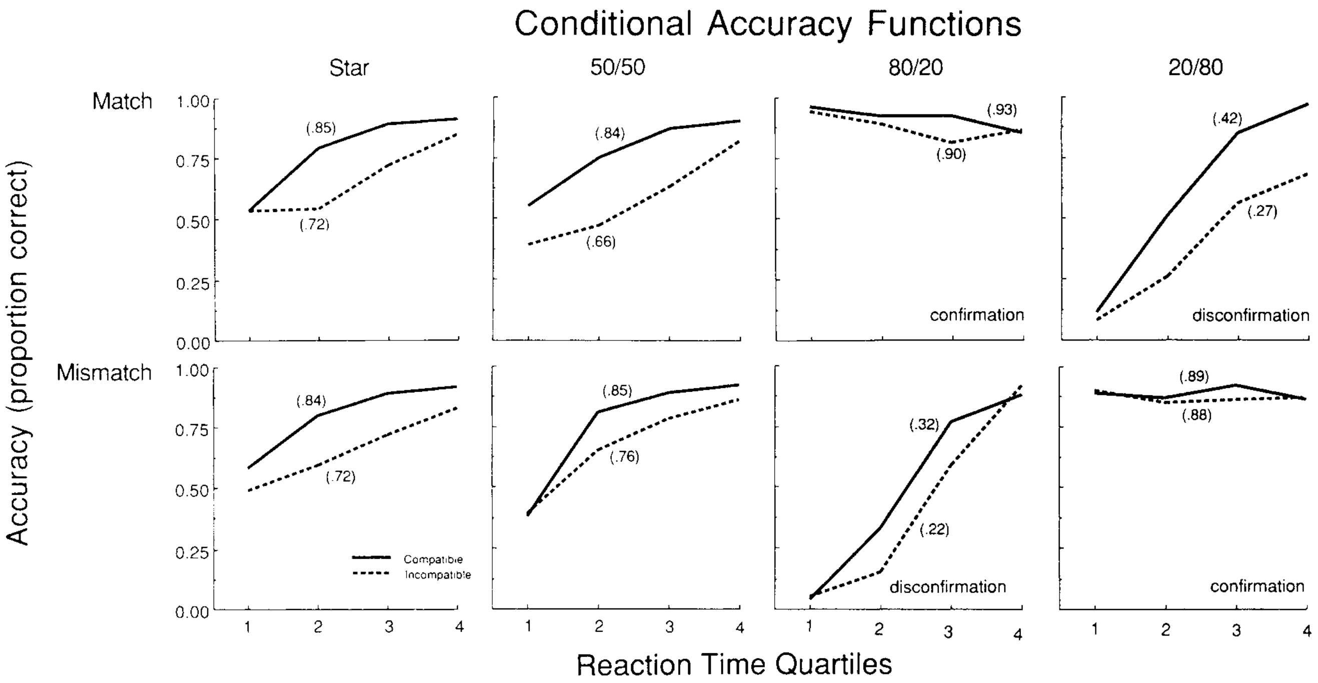

Figure 2. Plots of accuracy (proportion correct) for each condition, as a function of electromyographic onset latency quartile. (Mean proportion correct across all electromyographic onset latencies within each condition appears in parentheses.)

to which the correspondence between the warning stimulus and the imperative stimulus affected the latency and accuracy of the subjects' responses.

Match/Mismatch Differences in the Probability Effect

Reaction time. Figure 1 further indicates that the difference in RT between confirmation and disconfirmation trials was greater in the 80/20 condition than in the 20/80 condition. In other words, the benefit of a confirmation plus the cost of a disconfirmation was larger when the warning stimulus predicted a matching rather than nonmatching imperative stimulus. A planned comparison of these differences indeed indicated that the confirmation–disconfirmation difference was greater in the 80/20 condition (131 ms) than in the 20/80 condition (81 ms), $F(1, 7) = 12.04$, $p < .025$, $MS_e = 847.43$.

Conditional accuracy functions. In keeping with the RT results, Figure 2 suggests that the difference between confirmation and disconfirmation trials in the accuracy of first RT bin responses was greater in the 80/20 condition than in the 20/80 condition. Planned comparisons supported this interpretation, $F(1, 7) = 25.86$, $p < .001$, $MS_e = 0.032$.

Summary

The RT and conditional accuracy data indicate that the information provided by the warning stimulus affected the subjects' overt responses.[8] In the 80/20 and 20/80 conditions, when the target letter was consistent with the prediction made by the warning stimulus, subjects responded more quickly and with fewer errors than when the target disconfirmed the prediction. The analysis of accuracy as a function of RT bin demonstrates that the tendency to respond on the basis of the warning stimulus was greatest when the subjects made relatively fast responses.

It is interesting that the information provided by the warning stimulus appeared to be more potent when the warning letter was likely to reappear as the target letter in the imperative stimulus (i.e., in the 80/20 condition). This is evident

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[8] As expected, squeeze onset latency measures presented a scenario that was qualitatively the same as that for EMG onset measures. The effects of imperative stimulus factors on squeeze latency were of greater magnitude, however. For example, the overall noise compatibility effect on EMG onset latency was 15 ms; the compatibility main effect was marginally significant, $F(1, 7) = 3.97$, $p < .10$, $MS_e = 1{,}766.14$ (although note the interaction reported in the text). For squeeze onset latency, the effect was 20 ms; for the compatibility main effect, $F(1, 7) = 7.59$, $p < .05$, $MS_e = 1{,}663.20$. As another example, the Prediction Condition × Match/Mismatch interaction for EMG was significant, $F(1.73, 12.12) = 93.73$, $p < .001$, $MS_e = 658.16$. For squeeze onset, the corresponding ratio was significant, $F(1.69, 11.83) = 125.97$, $p < .001$, $MS_e = 612.43$. The mean difference between EMG onset latencies on match and mismatch trials was 131 ms in the 80/20 condition, whereas for squeeze onset the difference was 142 ms. In general, EMG onset preceded squeeze onset by about 40 ms: the EMG onset grand mean was 304 ms, and the squeeze onset grand mean was 345 ms. Of the trials classified as correct according to the EMG onset classification, 0.8% would have been classified as incorrect according to the squeeze onset classification. Of the trials classified as incorrect according to EMG onset, 18.1% would have been classified as correct according to the squeeze onset classification.

from the fact that there was a greater difference between the correct RTs associated with confirming and disconfirming responses in the 80/20 condition than in the 20/80 condition. There were corresponding effects on conditional accuracy functions. We note in passing that the data obtained in the Star and 50/50 conditions replicated the data of Coles et al. (1985) and of Gratton et al. (1988), who reported a significant effect of noise compatibility on RT and accuracy. However, the RT was not slowed by the presence of the incompatible noise in the 80/20 and 20/80 conditions. In these conditions, as is apparent from the mean correct RTs, subjects responded very quickly. When the predicted imperative stimulus occurred, they tended to respond correctly, regardless of the compatibility of the noise. Thus in these conditions, responses appear to be heavily influenced by priming processes.[9]

The overt response data indicate that the subjects prepared differentially for the imperative stimuli as a consequence of the information provided by the warning stimuli. These data do not, however, allow one to determine which of many modes of preparation, or rather what mix of such modes, the subjects were employing. For example, the difference between the confirmation/disconfirmation effects observed in the 80/20 and 20/80 conditions could be a result of differences in motor preparation, differences in perceptual preparation, or both. An examination of event-related potentials elicited by both the warning and the imperative stimuli can shed light on this issue.

Analysis of Event-Related Potentials

Motor Preparation: Probability Effects

To the extent that the effects observed in the overt response data were caused by motor preparation, the readiness potential during the foreperiod should have been larger over the hemisphere contralateral to the response predicted by the warning stimulus in the 80/20 and 20/80 conditions. As discussed earlier, the LRP was used as the measure of motor preparation. Figure 3 shows the LRP waveforms, averaged over the subjects, for each of the four predictive conditions separately. All trials are included, regardless of the accuracy of the response, and the average LRP from before the warning stimulus until 1 s after the imperative stimulus is shown. In the foreperiod, there was no net lateralization of the readiness potential in the 50/50 and Star conditions, which suggests that, on the average, subjects did not preferentially prepare a particular response in these conditions. In the 80/20 condition, beginning about 300 ms before the imperative stimulus, the lateralization favored the predicted response. This indicates that the predicted response was prepared during the foreperiod. In the 20/80 condition, foreperiod preparation was also evident, except that the lateralization was smaller at the time of the imperative stimulus and began somewhat later.

We quantified the LRP data by computing the mean value of the LRP measured over the 100 ms before the imperative stimulus for each trial of each predictive condition. These values were submitted to a repeated-measures ANOVA with predictive condition as a factor. A significant effect of predictive condition was found, $F(1.91, 13.36) = 20.11$, $p < .001$, $MS_e = 5.07$. Planned comparisons confirmed that the lateralization differed from zero in both the 80/20 condition, $t(7) = -6.39$, $p < .001$, one-tailed, and the 20/80 condition, $t(7) = 2.07$, $p < .05$, one-tailed. Lateralization did not differ significantly from zero in the STAR condition, $t(7) = -0.35$, $p > .25$, two-tailed, or in the 50/50 condition, $t(7) = -0.94$, $p > .10$, two-tailed.

If motor preparation was indeed contributing to the effects observed in the overt response data and if the LRP indexed this motor preparation, the LRP amplitude should be related to the accuracy of the subsequent response. Correct responses should have been associated with prior lateralization that suggests preparation of the correct response, and incorrect responses should have been associated with lateralization in the direction of the incorrect response. In order to test for such an effect, the LRP waveforms on mismatch trials were inverted, so that negative-polarity LRP values on all trials indicated that the LRP was more negative in amplitude contralateral to the correct response; this suggests relative preparation of the correct response (cf. Coles, 1989). These waveforms were then averaged according to two factors: the conditional probability of imperative stimulus occurrence (.80, .50, or .20) and the accuracy of response. Figure 4 depicts the resulting waveforms. Mean amplitude measures of the LRP, taken over the 100 ms epoch preceding the imperative stimulus, were submitted to a 3 × 2 (Probability × Accuracy) repeated-measures ANOVA. A main effect of accuracy was obtained, $F(1, 7) = 38.62$, $p < .001$, $MS_e = 7.51$, whereas the interaction between probability and accuracy was not significant, $F(1.88, 13.17) = 3.27$, $p > .05$, $MS_e = 10.87$. On correct trials, the LRP was significantly more negative contralateral to the correct response than on incorrect trials. Therefore, in all types of conditional probability trials, including those for which the warning stimulus delivered no explicit response information (as in the study by Gratton et al., 1988), the accuracy of the response was related to the lateralization of the LRP during the foreperiod.[10]

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[9] Note that noise compatibility did significantly affect the accuracy of slow responses (see Figure 2). Furthermore, visual inspection of the Vincentized cumulative distribution functions (CDFs) of EMG onset latencies suggest that most of the responses occurred before noise compatibility affected the reaction time distribution: The CDFs for compatible and incompatible arrays on confirmation trials are virtually identical from the left tail of the distribution to about the median EMG onset. After that the distributions separate, the incompatible distribution being more positively skewed. These observations support the inference that at early response latencies, subjects responded primarily on the basis of warning stimulus information. The responses occurred before noise information could have its usual effect.

[10] The LRP waveforms for the period after the imperative stimulus were also examined to determine whether the waveforms for incompatible trials would indicate that the incorrect response was initially activated after stimulus presentation. Such an effect was reported by Coles, de Jong, Gehring, and Gratton (in press); Gratton, Coles, Sirevaag, Eriksen, and Donchin (1988); and Smid, Mulder, and Mulder (1990). We focused on correct responses in the conditions most similar to those used in previous research (Star and 50/50). However, although the dip was apparent in the average waveform, it was not significantly different from zero.

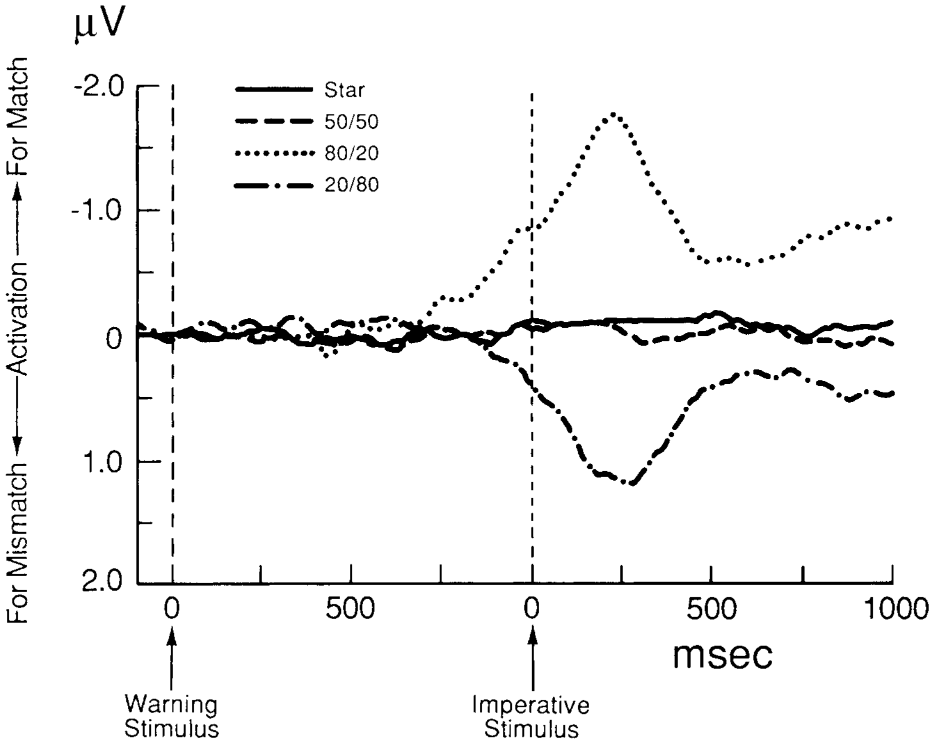

Figure 3. Grand mean lateralized readiness potential waveforms (see text) averaged according to predictive condition. (Msec = milliseconds. Negative values indicate preparation to respond to a letter that matches the warning letter, and positive values indicate preparation of the other response. Thus if *H* is the warning letter, negative values suggest preparation of the *H* response, and positive values suggest preparation of the *S* response; see Method section.)

Motor Preparation: Match/Mismatch Differences

As noted, there were marked differences between the 80/20 and 20/80 conditions in the patterns of RTs and accuracy. Specifically, the warning stimuli appeared to have a more pronounced effect during the 80/20 condition. To see whether the absolute level of lateralization differed between the 80/20 and 20/80 conditions, we performed a separate test in which we compared the absolute values of the LRP amplitude for the last 100 ms of the foreperiods in these two conditions. These data corresponded to the deviations from zero in the upward (80/20 condition) and downward (20/80 condition) directions at the end of the foreperiod shown in Figure 3. The analysis indicates that the preparation in the two predictive conditions did indeed differ, $t(7) = 3.39$, $p < .02$, two-tailed. Thus the absolute level of response preparation was greater when the warning letter predicted that the imperative stimulus would be the same letter (80/20 condition) than when the warning predicted the opposite letter (20/80 condition).

Perceptual Preparation: The N200

As we discussed earlier, perceptual processing may also facilitate appropriate preparation. The N200 component appears to manifest a process that is sensitive to preparatory information: It is larger in response to improbable stimuli than to probable stimuli. On the basis of studies of the visual N200, however, it is unclear whether the stimulus features that violate the subject's expectancy must be conjoined to designated visual locations in order to elicit the N200.

According to one hypothesis, the N200 manifests processing that is sensitive to the mismatching stimulus features only when they are conjoined to designated visual locations. By this account, the N200 should have been larger on disconfirmation trials in the 80/20 and 20/80 conditions, and the surrounding noise letters should have had no effect. A second hypothesis (inspired by the work of Treisman and her colleagues; e.g., Treisman & Gormican, 1988) is that the effects of stimulus probability on the N200 represent processing that is sensitive only to the occurrence, not to the locations, of particular stimulus features. In this case, the N200 should have displayed a graded effect: Its amplitude should increase as a function of the number of letters in the array that are different from the predicted target letter. The target or noise status of the letters should not matter. Thus in the 80/20 condition, the largest N200 should occur on mismatch compatible trials and the smallest N200 on match compatible trials, the amplitude of the N200 on the incompatible trials being intermediate. A complementary set of predictions can be made for the 20/80 condition.

The waveforms shown in Figure 5 favor the hypothesis that the effect of probability information was independent of the target or noise status of the letters. In each predictive condition

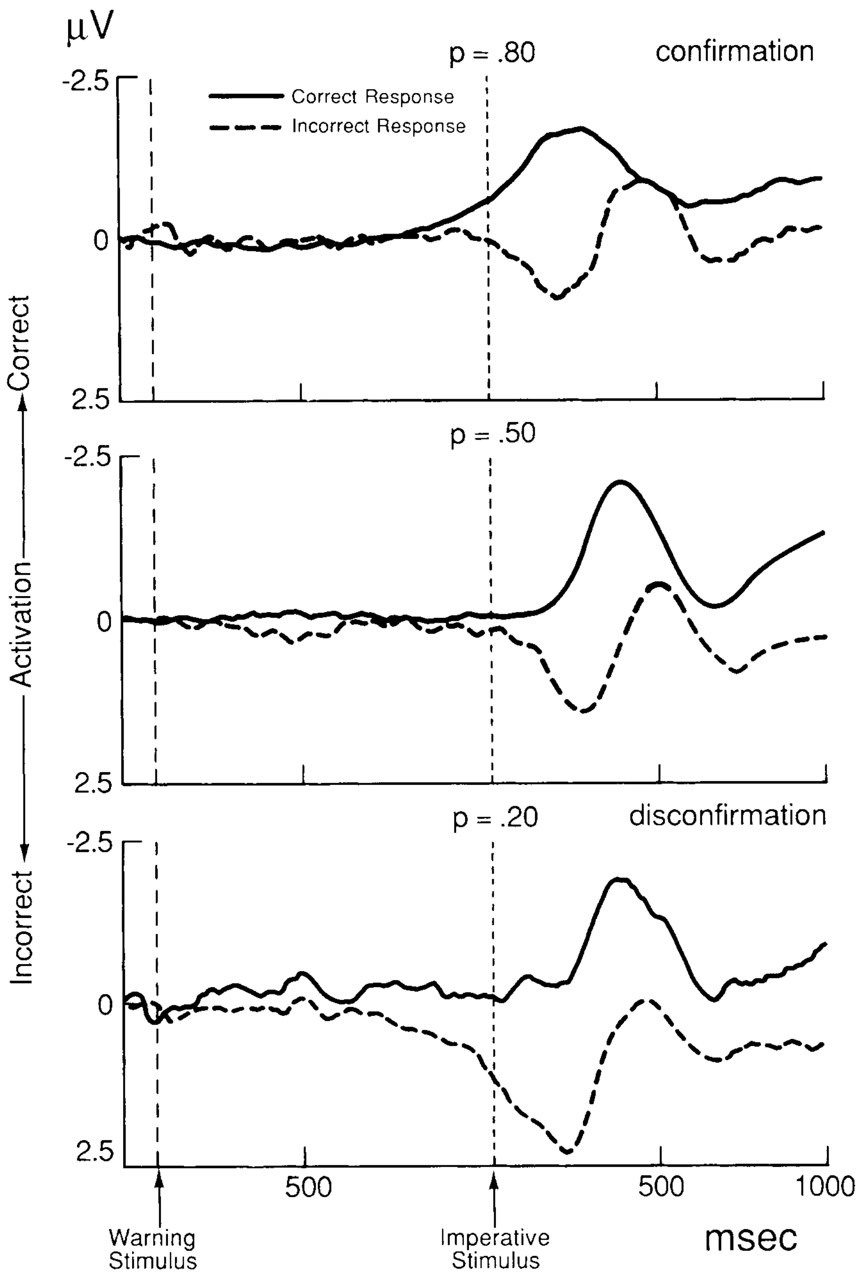

Figure 4. Grand mean lateralized readiness potential waveforms averaged according to the probability of occurrence of the imperative stimuli and the accuracy of the response. (Msec = milliseconds. The waveforms are plotted in such a way that a negative value indicates relative preparation of the correct response and a positive value indicates relative preparation of the incorrect response. The p = .50 waveforms represent trials pooled across the Star and 50/50 conditions, and the p = .80 and p = .20 waveforms are pooled across the 80/20 and 20/80 conditions. On incorrect response trials, subjects sometimes executed the correct response after their initial error. This is responsible for the late deflection toward the correct direction on these trials.)

(80/20 and 20/80), the smallest N200 occurred when all the letters in the visual array matched the expected target letter (match/compatible in the 80/20 condition and mismatch/compatible in 20/80 condition), and the N200 amplitude increased as a function of the number of letters that differ from the expected target letter. For example, in the match/incompatible case in the 80/20 condition, the target letter was actually the one predicted by the warning information, and yet the presence of several letters different from the probable target letter elicited a large N200.

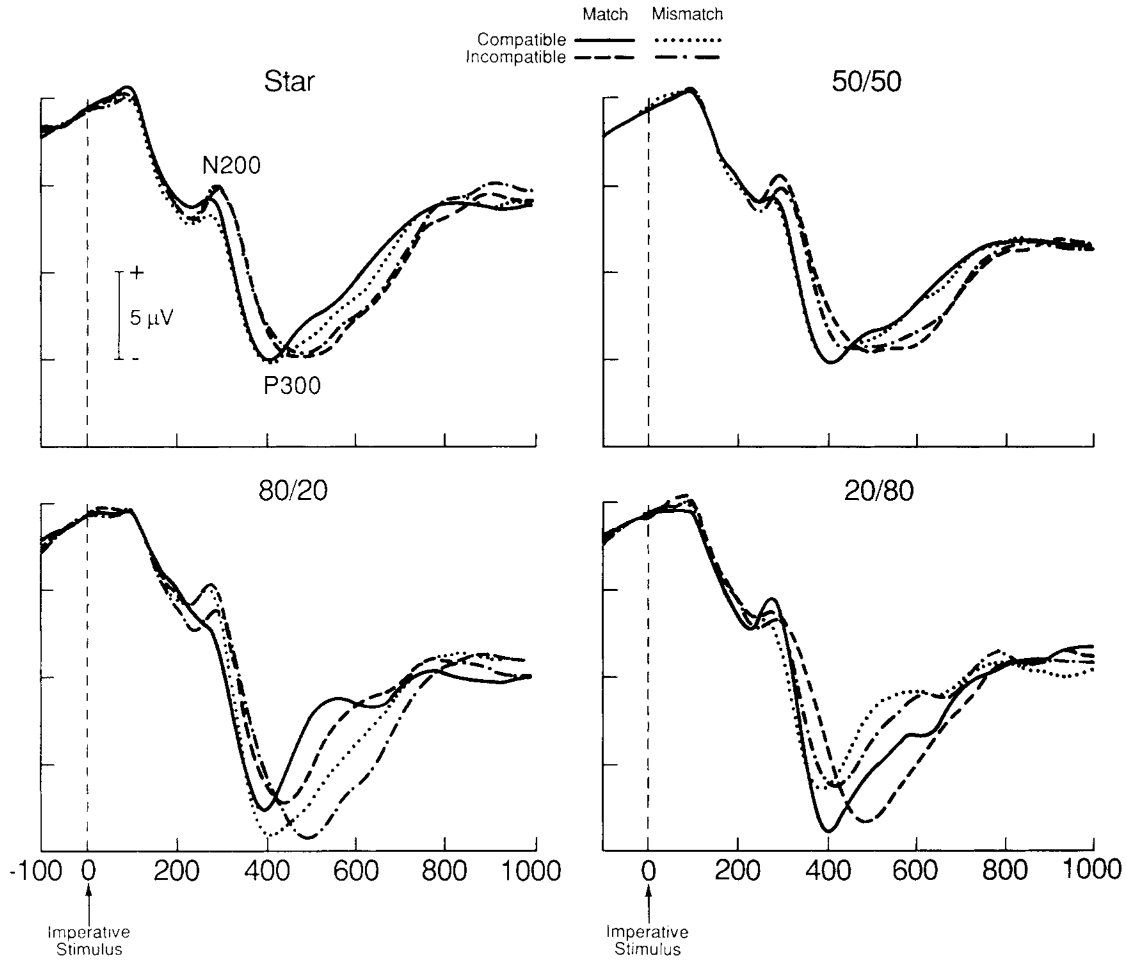

Figure 5. Average waveforms recorded at the Cz electrode location for an epoch beginning 100 ms before the imperative stimulus. (The N200 activity is evident as a negative-going deflection at approximately 250 to 350 ms after the onset of the imperative stimulus.)

We quantified these effects by calculating the mean amplitude at Cz over the 250- to 350-ms epoch that followed the imperative stimulus. The measures were submitted to a 4 × 2 × 2 (Predictive Condition × Match/Mismatch × Compatibility) repeated-measures ANOVA. A Predictive Condition × Match/Mismatch × Compatibility interaction was obtained, $F(2.09, 14.63) = 5.83$, $p < .025$, $MS_e = 60.05$. A planned analysis of linear trend supported the impressions noted earlier for the 80/20 condition, $F(1, 7) = 11.10$, $p < .025$, $MS_e = 92.34$, although in the 20/80 condition the linear trend did not achieve significance, $F(1, 7) = 2.65$, $p > .10$, $MS_e = 159.53$. Thus in the 80/20 condition, the N200 increased in the following order (from smallest to largest): match/compatible, mismatch/incompatible, match/incompatible, and mismatch/compatible. In addition, subsequent post hoc comparisons revealed that the N200 at Cz was larger in response to incompatible arrays than to compatible arrays in the Star condition, $F(1, 7) = 22.59$, $p < .0025$, $MS_e = 92.78$, and in the 50/50 condition, $F(1, 7) = 34.81$, $p < .001$, $MS_e = 63.99$.

Details in Figure 5 suggest several problems with accepting these conclusions at face value. The presence of multiple components makes the N200 data somewhat difficult to interpret. The N200 effects could be attributable to some extent to effects of the overlapping P300 component. For example, a delay in the P300 could make the N200 appear larger. Moreover, the data suggested that the pattern and timing of effects was different at the Fz electrode (not shown in the figure) than at the Cz electrode. N200-like activity at Fz lasted longer than the N200 activity at Cz. Because the time course of the waveforms is different at the two electrode sites, it appears that two negative components may be distinguished in the region of the N200; one is largest at the central electrode, and the other is maximal at the frontal electrode.

We used the vector filter procedure described by Gratton, Coles, and Donchin (1989) to disambiguate the multiple components in the N200 region. The filter extracts components that have particular scalp distributions from the original waveforms. In use of this technique, it is assumed that the amplitude of each data point of the Fz, C3′, Cz, C4′, and Pz waveforms can be described as a linear combination of the amplitudes of several underlying components: in our study, a negative component maximal at Fz, a negative component maximal at Cz (the N200), and a parietally maximal positive component (the P300). For each time point, a multiple regression procedure is used in the vector filter to determine the amplitude of each hypothesized component, so that the linear combination of the amplitudes of all the components minimizes the error in predicting the observed voltage values at Fz, Cz, C3′, C4′, and Pz. As a result, the vector filter outputs one waveform for each hypothesized component, and the amplitude measure for each component can be derived from the corresponding waveform for that component.[11] To obtain a measure of amplitude for the frontal negative component, we computed the average amplitude of the vector-filtered waveform for a 300- to 450-ms epoch after the imperative stimulus. For the central component (N200) waveform, we computed the average amplitude over a 200- to 300-ms epoch. For the P300 component, we selected the value of the positive peak of the waveform within a 300- to 700-ms epoch.

The cell means derived from the filtered waveforms are shown in Figure 6. Mean amplitude measures of the frontal component were submitted to a 4 × 2 × 2 (Predictive Condition × Match/Mismatch × Compatibility) repeated-measures ANOVA. A main effect of noise compatibility, $F(1, 7) = 22.42$, $p < .005$, $MS_e = 430.03$, indicated that the amplitude of this negative component was larger when the array was incompatible. The lack of an interaction between compatibility and the other experimental conditions suggests that the amplitude of this component was sensitive to whether the target and the noise letters were the same but insensitive to the relationship between the noise letters and the expectancies for particular target letters.

Of more interest in our analysis was the N200 component whose amplitude was largest at the central electrode. Mean amplitude measures were submitted to a 4 × 2 × 2 (Predictive Condition × Match/Mismatch × Compatibility) repeated-measures ANOVA. As suggested by the cell means in Figure 6, noise compatibility did not have a main effect on the central component (in contrast to the frontal component described earlier), $F(1, 7) = 0.90$, $p > .05$, $MS_e = 193.27$. An interaction was observed between predictive condition, match/mismatch, and compatibility, $F(1.56, 10.90) = 8.77$, $p < .01$, $MS_e = 105.69$. Inspection of Figure 6 suggests that the amplitude of the component in the 80/20 condition increased in the following order (from least to most negative): match/compatible, mismatch/incompatible, match/incompatible, and mismatch/compatible. The presence of a significant linear trend, $F(1, 7) = 33.49$, $p < .001$, $MS_e = 80.31$, was consistent with these observations. Thus the amplitude of the component became larger as a function of the number of letters in the array that did not correspond to the letter predicted by the warning stimulus.

We expected the ordering of amplitudes in the 20/80 condition to be precisely the reverse of that in the 80/20 condition. Indeed, Figure 6 suggests that the ordering is as follows (from least to most negative): mismatch/compatible, match/incompatible, mismatch/incompatible, and match/compatible. The corresponding analysis of linear trend for the 20/80 condition, however, was not significant, $F(1, 7) = 1.04$, $p > .10$, $MS_e = 352.34$.

Taken together, the 80/20 and 20/80 results suggest that an expectancy established by the warning stimulus for particular letters, regardless of their status as target or noise, was the principal determinant of the N200. Thus it appears that the process manifested by the central N200 is sensitive to the identities of the stimuli in the visual field but not to their locations. A later, more frontal component appears to be sensitive to the noise compatibility manipulation and to be independent of expectancy for the target letter.

Other Forms of Preparation: The P300

We examined the amplitude of the P300 elicited by the imperative stimulus to determine whether the subjective probability of the imperative stimuli was indeed affected by the warning stimulus information, as in Duncan-Johnson and Donchin's (1982) study. We thus anticipated that the more probable events in the 80/20 and 20/80 conditions would elicit P300s with smaller amplitudes. P300 amplitude measures were submitted to a 4 × 2 × 2 (Predictive Condition × Noise Compatibility × Match/Mismatch) repeated-measures ANOVA. Figure 6 indicates that in the 80/20 condition, P300 amplitude was larger on mismatch trials than on match trials and that in the 20/80 condition, P300 was larger on match trials than on mismatch trials. (The P300 amplitudes on match and mismatch trials did not differ in the STAR and 50/50 conditions.) A significant Predictive Condition × Match/Mismatch interaction was found, $F(1.45, 10.18) = 7.03$, $p < .025$, $MS_e = 634.97$. Planned comparisons supported the pattern outlined earlier, although the critical comparison in the 20/80 condition did not achieve significance: In the Star condition, $F(1, 7) = 0.02$, $p > .10$, $MS_e = 66.53$; in the 50/50 condition, $F(1, 7) = 1.13$, $p > .05$, $MS_e = 191.14$; in the 80/20 condition, $F(1, 7) = 11.25$, $p < .025$, $MS_e = 1{,}057.25$; and in the 20/80 condition, $F(1, 7) = 2.17$, $p > .05$, $MS_e = 1{,}185.46$.

These results indicate that P300s were larger when target stimuli disconfirmed the prediction of warning stimuli. The warning–target relationship made no difference when the warning was uninformative, however. Moreover, no significant main effects or interactions involving the noise compatibility manipulation occurred.[12]

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[11] The vector filter weights used were the following (see Gratton, Coles, & Donchin, 1989): Fz maximal negative component: −0.640*Fz − 0.426*Cz − 0.213*Pz − 0.426*C3′ − 0.426*C4′; Cz maximal negative component: −0.267*Fz − 0.535*Cz − 0.267*Pz − 0.535*C3′ − 0.535*C4′; Pz maximal positive component: 0.213*Fz + 0.426*Cz + 0.640*Pz + 0.426*C3′ + 0.426*C4′.

[12] An analysis of the corresponding P300 latency values revealed a main effect of noise compatibility, $F(1, 7) = 86.03$, $p < .001$, $MS_e = 338.28$, and an interaction between predictive condition and match/mismatch, $F(2.18, 15.26) = 23.94$, $p < .001$, $MS_e = 936.20$. Compatible arrays were associated with shorter P300 latencies (420 ms) than were incompatible arrays (450 ms; cf. Coles, Gratton, Bashore, Eriksen, & Donchin, 1985). In the 80/20 and 20/80 conditions, P300 latencies on confirmation trials were shorter than those on disconfirmation trials (cf. Duncan-Johnson & Donchin, 1982): in the 80/20 condition, $F(1, 7) = 15.96$, $p < .01$, $MS_e = 1{,}657.14$; in the 20/80 condition, $F(1, 7) = 25.81$, $p < .0025$, $MS_e = 1{,}545.98$.

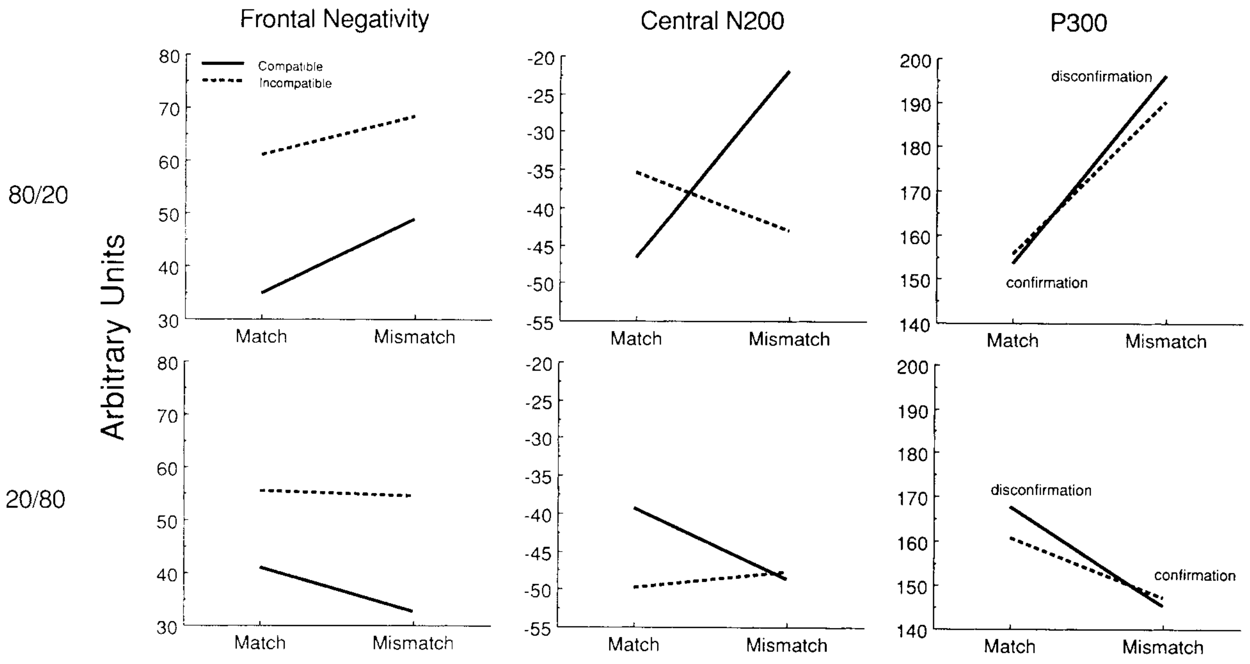

Figure 6. Cell means for three event-related brain potential component measures derived by means of the vector filter procedure (see text): a frontally maximal negative component, a centrally maximal N200, and the parietally maximal P300. (For each component, the more positive, or less negative, the value is, the larger the amplitude is, regardless of the polarity of the component.)

Summary

The LRP data suggest that the response predicted by the warning stimulus in the predictive conditions was prepared during the foreperiod. Furthermore, the degree of preparation was greater when the warning letter was likely to reappear as the target letter than when the opposite letter was likely. These inferences were based on an examination of the LRP during the last 100 ms of the foreperiod.

The N200 data point to the presence of preparatory effects that relate to the expectancy for particular letters, regardless of their status as targets or noise. It appears that there was a perceptual process that was tuned to expect the letter predicted by the warning stimulus, but this process was insensitive to whether the letter occurred at the target location. These inferences are based on the fact that the amplitude of the N200 depended on the number of letters in the imperative stimulus that did not match the predicted letter. In contrast, the P300 data suggest the presence of another perceptual process that *was* tuned to expect a particular letter in a particular (target) location. The P300 was larger when the target letter was not predicted.

Finally, the N200 data also suggested the presence of a process that was independent of preparatory effects. This process was sensitive only to the relationship among the letters presented at the imperative stimulus and was suggested by the observation that a frontal negativity was sensitive only to the compatibility manipulation.

Discussion

We assessed priming effects in a choice RT task in which subjects received information regarding the probability of occurrence of particular stimuli. We used psychophysiological measures in an effort to localize the effects of advance information on distinct parts of the information-processing system.

The overt response data confirmed that subjects used the information provided by the warning stimuli. Reaction times were faster and error rates were lower when subjects received an imperative stimulus that had been predicted by a warning stimulus than when the imperative stimulus was not predicted by the warning stimulus. The tendency to respond according to the warning stimulus information was greatest for fast responses. These overt behavioral effects were more pronouced when the warning stimulus predicted the same stimulus (80/20 condition) than when it predicted a different stimulus (20/80 condition). These data indicate that preparatory activity did occur in response to informative warning stimuli. However, the data do not reveal whether this preparatory activity affected the motor system, the perceptual system, or both.

Furthermore, although there were clear differences between the 80/20 and 20/80 conditions in RT and in conditional accuracy functions, these behavioral results do not necessarily imply that the difference was caused by differential preparation in the two conditions.[13] Suppose that responses are faster when the warning stimulus and the imperative stimulus match, regardless of whether the imperative stimulus in fact confirmed the prediction of the warning stimulus. Such a stimulus match effect would increase the benefits of confirmation and the costs of disconfirmation in the 80/20 condi-

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[13] We thank David Meyer for drawing our attention to this possibility.

tion in relation to the 20/80 condition. Thus the overt behavioral data cannot pinpoint what processing loci are prepared and whether preparation is the same or different in the two conditions. This ambiguity points to the need for measures that are sensitive to the effects of preparation on specific information-processing subsystems.

The ERP measures provide this kind of specificity and, in this study, pointed to several elements of the information processing system that were prepared as a consequence of warning stimulus information. We investigated motor preparation by examining the LRP. The LRP indicated that subjects prepared the response predicted by the warning stimulus information. Moreover, the direction of lateralization in the period preceding the stimulus was related to the accuracy of the response after stimulus. Thus when stimuli that disconfirmed the warning stimulus prediction were presented, subjects responded more accurately if they had not prepared the predicted response than if they had. These LRP results indicate that motor preparation can be manipulated by the provision of advance response information and that this preparation affects the characteristics of the subsequent response.

The time course and the extent of motor preparation varied according to how information was presented to the subject. In the 80/20 and 20/80 conditions, the information (in an information-theoretical sense) presented by the warning stimulus was the same, and yet the amount of motor preparation, as manifested by the LRP, differed. Hence the difference between these conditions in the effects of warning information on overt behavior appear to be at least partially attributable to a difference in motor preparation. Such a difference could have arisen from strategic differences on the part of the subject or from a difference in the amount of time necessary to transform a representation of the warning stimulus to a representation of the predicted response. In any case, the LRP data allowed us to localize the behavioral difference to a specifically response-related element of the information-processing system.

We also examined the effects of preparation on mechanisms involved in evaluating the stimulus. In particular, we were able to distinguish between two hypotheses regarding the presetting of the perceptual process manifested by the N200 component of the ERP: (a) that the process is sensitive only to a mismatch between the physical identities of the predicted stimulus and the imperative stimulus and (b) that the process is sensitive to a mismatch between the physical identities and the visual locations of both the predicted stimulus and the imperative stimulus. In other words, the central question was whether the N200 was evoked by the appearance of noise stimuli that were not in the location to which the subject had to respond but that nevertheless mismatched the predicted stimulus.

The results suggest that the process is sensitive to only the identities, not the locations, of letters present in the visual field. When the warning stimulus offered predictive information, the information primed this process, in such a way that the amplitude of the N200 increased as a function of the number of letters that were different from the letter predicted by the warning stimulus, regardless of their visual locations. These results lend themselves well to an interpretation that is consistent with the pooled-response model of Treisman and Gormican (1988) and Treisman and Souther (1985), an extension of Treisman and Gelade's (1980) feature-integration theory of attention. On the basis of research involving visual search tasks, Treisman and her colleagues hypothesized that a feature-analysis system, operating before focused attention, codes stimulus features as departures from standard or prototypical feature values before the features are conjoined to their visual locations. Standard or prototypical stimuli elicit the smallest amount of feature-coding activity. Thus in the visual search task, one detects deviant stimuli simply by determining whether feature-coding activity is present. Detection of standard stimuli must, in contrast, rely on focused attention to conjoin features to visual locations because the stimuli do not elicit feature-coding activity.

Within this scheme, the interpretation of the process manifested by the N200 is straightforward. It is clear, from our data and from the data of Duncan-Johnson and Donchin (1982), that the process manifested by the N200 is tuned according to the information presented in an informative warning stimulus. The results of our study suggest that this process is sensitive to feature identities (or at least letter identities) and not to feature locations. Hence if this process is indeed involved in the feature analysis posited by Treisman and her colleagues, the behavior of the N200 suggests that the feature-analysis system may be tuned, or primed, by warning stimulus information. Although further work must take place before the N200 can be unequivocally linked to feature analysis, it is instructive to note how the amount of N200 activity mimics the pattern of feature-analysis activity that would be predicted if the feature-analysis system could be primed in this manner: The predicted letters in our task would elicit the smallest amount of feature-detection activity, regardless of their locations, like the prototypical stimuli in Treisman's work. Letters corresponding to violations of the prediction, like Treisman's deviant stimuli, would elicit the largest amount of activity.

These results were made clearer by removal of the effects of a later, overlapping frontal negativity that was sensitive to noise compatibility and insensitive to the relation between the warning and imperative stimuli. The results, however, did not depend on the use of the vector filter procedure. The critical analysis of linear trend was significant in the 80/20 condition both in the raw waveforms and in the vector-filtered waveforms.

We do not intend to assert that the N200 effects are necessarily *priming* effects. In the overt behavior, we observed no significant interaction that paralleled the effects observed in the N200. It is therefore difficult to attribute part of the overt behavioral costs and benefits to the modulation of the process manifested by the N200. Improving the efficiency of a process results in changes in overt behavior only if the improvement allows response-related processing to begin earlier or to be accomplished more efficiently. It is therefore possible for an ERP component to appear large in response to improbable stimuli without being associated with overt behavioral changes. For example, processes necessary for performance in the current trial might not use the output of the process manifested by an ERP. Instead, other subsystems, concerned more with strategic information processing (Donchin, 1981) than with the current trial, might use the output.

These mismatch effects thereby suggest that probability information changed the workings of some aspect of the information-processing system. What role these changes have, be it strategic or otherwise, is yet to be determined.[14]

Replicating the results of Duncan-Johnson and Donchin (1982), we found that the P300 component was larger when stimuli disconfirmed the prediction of an informative warning stimulus than when they confirmed the prediction. Thus the process manifested by the P300 was preset on a trial-to-trial basis by an informative warning stimulus. This result suggests that the warning stimulus induced subjects to generate expectancies regarding the probability that particular target letters would occur. The P300 data are distinct from the N200 data in that only the target letter determined the priming effects on P300; the relationship between the warning stimulus information and the noise letters surrounding the target did not affect P300 amplitude. The sensitivity of the P300 to probability information was therefore dependent on the locations as well as the identities of the letters.

To summarize, we have demonstrated how measures of ERPs can be used to localize the effects of probability information in a warned RT task. The results implicate both perceptual and motor processes as loci for probability effects. Moreover, the use of ERPs allowed us to examine a situation in which both stimulus probability and response probability may have exerted an effect. These data complement and extend those obtained with elaborations of traditional overt behavioral methods (e.g., Meyer et al., 1984, 1985) and with neurophysiological techniques (e.g., Requin, 1985; Requin, Lecas, & Bonnet, 1984) and, perhaps more important, serve to bridge the two approaches.

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[14] A similar dissociation between an ERP component and overt behavior is evident in the effect of noise compatibility in the 80/20 and 20/80 conditions. Here P300 latency is longer for incompatible arrays, but the mean RT latencies are not. As we argued earlier (Footnote 9), an analysis of the Vincentized cumulative distribution functions (see also the conditional accuracy functions in Figure 2) suggests that in these predictive conditions, subjects did not use all the information provided by the imperative stimulus to guide their responses (except when they responded slowly). On the other hand, previous research on the P300 (see Donchin & Coles, 1988, for review) indicates that the P300 is not emitted until after the full evaluation of the stimulus. For this reason, the observed dissociation is not surprising.

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Neuropsychology to Be an APA Journal

In January 1993, *Neuropsychology*, which has been published by the Educational Publishing Foundation (a subsidiary publishing program of the American Psychological Association), will be published by the American Psychological Association. The Publications and Communications Board of the APA has appointed Nelson Butters as editor of *Neuropsychology*. As of January 1, 1992, manuscripts should be submitted to

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