

3 *Event-Related Brain Potentials in the Study of Consciousness*

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I. INTRODUCTION

A. A Phenomenological Approach to Consciousness

The electrical activity of the brain has always tantalized investigators interested in developing a psychobiology of consciousness. Hans Berger had been driven to his pioneering studies of the human electroencephalogram (EEG) by his interest in "psychic energy." Jung (1975) reported that Berger "believed that the chemical energy of brain metabolism was transported into heat, electrical and 'psychic' energy, and he hoped to extrapolate the latter by measuring the heat production and electrical activity of the brain" (p. 484). The EEG, which Berger discovered, promised to allow insights into the mechanisms underlying consciousness. The rationale for this promise is evident. Because the phenomena of consciousness make themselves most readily available in the human, consciousness is best studied in the awake, alert, speaking individual. As electrical brain activity is one of the few means available for the observation of neural activity in the intact human, it is a natural object of interest to the student of consciousness.

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In this chapter, we review studies of event-related brain potentials (ERPs) that address, either explicitly or implicitly, the phenomena of consciousness. An analysis of the methodology and findings of these studies leads to an examination of their conceptual foundations. It is our contention that these studies can benefit from recognizing the fundamental difference between the data on consciousness and the data on brain potentials. The data on consciousness take the form of introspective reports. That is, subjects report, either in words or by the manipulation of mechanical devices, about their consciousness. They may press a button labeled *red*, or state "the red light was on," or report the number of times the red light was illuminated over a period of time. The datum provided by the subject is the *product* of multiple brain processes, conscious and nonconscious. Electrical brain activities recorded on the scalp are, on the other hand, data on one or more of the *processes* that may be involved in conscious experience. We shall endeavor to show how this distinction between processes and their products, if used to guide research in cognitive psychophysiology, might lead to a firmer foundation for the development of a psychobiology of consciousness.

We adopt in this chapter a phenomenological approach to consciousness. That is, we accept that the data generated by our own and by others' reports about consciousness define a *phenomenon*. This phenomenon is as valid an object for analysis as any other phenomenon defined by any other data base. The individual's statement "I am aware . . ." is as valid a datum as the observation that a rat has locomoted on all fours down an alley in a maze. Observations define phenomena and it is the scientists' privilege to select those that appear to be—perhaps for personal reasons—the most exciting or promising. It is the scientists' responsibility, however, to treat the phenomenon chosen for study with ruthless objectivity, untrammled by religious or philosophical predilections.

Our use of the term *introspection* requires a word of explanation. This perfectly appropriate word, which lexically means "self-report," carries to the psychologist a load of excess meaning. It invokes introspectionism, the once dominant force in American and German psychology (Boring, 1957). Yet the difference between contemporary cognitive psychology and Titchenerian introspectionism is not that one does, and the other does not, abjure introspection. Rather, the two differ in the way that they use introspective data. For both disciplines, the prime data are the reports an individual makes about his or her consciousness. The Titchenerians, however, viewed themselves as observers of the phenomenon. Their introspective reports described consciousness in the same way that Lewis and Clark described the North-

west. Here, for example, is Titchener's (1905) psychologist:

A man keenly interested in mind, with no purpose beyond mind; a man enamored of introspection; a man to whom the most fascinating thing in the universe is the human consciousness; a man to whom successful analysis of an unresolved mental complex is as the discovery of a new genus to the zoologist or a new river to the explorer; a man who lives with his mental processes as the naturalist lives with creatures which are ordinarily shunned or ignored. (p. 220)

According to this view, it is the psychologist's task to become a skillful observer of his or her own consciousness. A psychologist who has achieved the status of a good observer can say, "This light has the quality of redness," and his statement must be taken as a valid description. The datum is "In Titchener's consciousness, this light has redness." For the contemporary student of introspection, on the other hand, the datum would be "Titchener *said* that the light is red." The difference between the two statements is fundamental. The cognitive psychologist views the introspective data not as if they were official reports about the state of consciousness but rather as an intelligence officer treats the multiple (often conflicting) reports received from the field. All need to be judged, compared, and sifted until a coherent view emerges. Therefore, the cognitive psychologist must rely on the highly structured framework of experiments to make sense of the data.

The reader will note that by emphasizing introspective reports, we are finessing a set of problems that lie at the core of a wondrously erudite philosophical literature. We do not presume to deny or affirm the importance and relevance of the philosophy of the mind and the fine distinctions between monism, dualism, interactionism, and various other approaches to the philosophical analysis of the concept of consciousness. Rather, we take in this chapter the position that this debate is not crucial to a discussion of the psychobiology of consciousness. We view the latter as an attempt to understand, in the terms of biology, the phenomena of consciousness. We leave the philosophically qualified to discourse on the reality of the mental, or on the possibility of mind-matter interactions. There is, however, one philosophical bias that guides our thinking that must be made explicit.

In considering the psychobiology of consciousness, we assume that the phenomena of consciousness are intimately associated with neural activity. This is hardly a novel statement. Yet, it will become important in our delineation of research programs utilizing ERPs to make it quite clear that we consider consciousness an aspect of neural activity. We view consciousness as a manifestation of brain activity that reveals itself through the methods of introspection. Depending on the measuring instrument, brain activity manifests itself as chemical events, graded

and pulsatile electrical events, temperature changes, and a host of other observables. Introspective reports can be viewed as yet another of these measures of brain activity. The following analogy might clarify our view. Consider the neuronal impulse as it appears to two investigators. The first, an electrophysiologist, places two electrodes on a neuron and records a potential difference between these electrodes in response to a stimulus. Such a study results in a description of neuronal activities in terms of pulse trains. A biochemist observes the neuron with a different set of tools and describes the events in terms of the movement of ions across membranes, the opening of pores in the membranes, and other, essentially chemical, descriptors. The two views of the neuron would, in many ways, be discrepant. In fact, the different techniques might dictate differences in the questions raised by the two investigators. Yet, neither of the two descriptions is inherently more valid, more fundamental, or more "phenomenal" than the other. Different methodologies yield different descriptions of the same phenomenon. It is, of course, of interest, once one accepts the assumption that the chemical and the electrical description of the neuron are both manifestations of the "same" phenomenon, to try to elucidate the relation between the two sets of observations. Such an endeavor is the study of electrochemistry. Concepts are developed that relate electrical and chemical concepts. Methods must be devised that allow the concurrent and closely related measurement of electrochemical events. Ultimately, this approach leads to a better understanding of neuronal function. Yet, it would be wasteful of intellectual energies to debate whether the electrical or the chemical are "epiphenomenal" to the real phenomena of neural function. To argue that the electrical manifestations of neural transmission are epiphenomenal because the process is ionic in nature is not particularly edifying. Even if it were conclusively established that the voltages associated with neural transmission are without causal relation to neural activity, these voltages remain an important manifestation of the process, and in an appropriately designed research program, these "epiphenomena" can provide crucial data about the organization of the nervous system.

It is in the spirit of this analogy that we approach the psychobiology of consciousness. Introspective reports are only one way of approaching brain activity. Reports of conscious experience become, in this view, a set of measurements of brain activity. Other measures of brain activity yield a different view of the brain. The two different ways of looking at the "same thing" must somehow be related. The relations will be elucidated through the forging of concepts that can deal with the joint variances of the two bodies of measurement. Techniques must be de-

veloped that will allow the study of such variance, and ultimately, given success, a more comprehensive understanding of the brain will emerge as the disparate phenomenal descriptions of its activity are unified.

This, then, is our object in pursuing the relation between ERPs and consciousness. It is because introspective reports can be obtained most readily from humans that the study of consciousness has the human at its focus. Neural activity in the human can be observed by other means only under fairly severe restrictions. It is not possible to subject human nervous systems to the mechanical, electrical, or chemical interventions that have been found so useful in the study of the nervous systems in nonhuman species. Neuropathology has provided richer data on human nervous activity. The administration of drugs is another important neuropsychological tool. Yet, these approaches are strongly limited by obvious ethical considerations. There remains only one rich source of data on neural activity in the awake, alert, behaving human: the recording from the scalp of the electrical activity of the brain.

B. The Event-Related Brain Potential: A Brief Survey

We limit ourselves in this chapter to a discussion of event-related brain potentials (ERPs). There is a large and interesting literature that focuses on the relation between the "ongoing" EEG and consciousness (see Lindsley, 1960; John, 1967). Work in that tradition dates to Berger's original studies. It tends to express the electrophysiological measurements in terms of their spectral composition and the observations on consciousness in terms of general states ("Is this person conscious? alert? comatose?"). Our research has focused on a different aspect of scalp-recorded electrical brain activity: event-related brain potentials. The ERP is a transient series of voltage fluctuations generated in brain tissue immediately preceding or following the occurrence of an event. This activity appears as a sequence of positive and negative peaks whose timing and relative magnitudes depend on the eliciting event, the state of the subject, and the placement of the recording electrode on the scalp (see Callaway, Tueting, & Koslow, 1978, for a comprehensive review of the ERP literature).

A central concept in the interpretation of the ERP waveform is the "component." Each peak-to-trough, or base-to-peak, deflection appearing in the ERP at a consistent interval following the eliciting event is often considered a component. More recently, components have been defined somewhat more rigorously as segments of the variability of the ERP waveform that are demonstrably controlled by experimental ma-

nipulations (Donchin, Ritter, & McCallum, 1978). The ERP waveform should definitely be treated not as a unitary object but as a sequence of overlapping components, each reflecting the activity of a neural processor.

A useful, heuristic distinction can be made between two classes of ERP components. Some components are *exogenous*. They represent an obligatory response of the brain to input in sensory channels. A series of seven wavelets can be recorded, for example, from the top of the head immediately following an auditory stimulus. The amplitude of these components is so minute that a signal average based on thousands of stimuli must be used for their extraction. These components seem to represent activity in the earliest stations of the auditory pathway (Starr, Sohmer, & Celesia, 1978). These brain-stem potentials have proved robust to manipulations of the subject's state. No matter how aroused, alert, asleep, relaxed, or attentive is the subject, the brain-stem evoked responses maintain their amplitudes and, generally, their latencies. However, damage to the auditory nuclei in the brain stem frequently causes specific distortions in the waveform of these evoked responses. It is for this reason that these early components have become important tools in neurological diagnosis.

The exogenous components are often followed by the *endogenous* components. These components represent information processing *invoked* by the psychological demands and the context in which a stimulus is presented, rather than that *evoked* by the presentation of stimuli. The amplitude, latency, and scalp distribution of these components reflect, in a systematic manner, variations in the underlying psychological substrate. It is characteristic of the endogenous components that they are *not* obligatory responses to stimuli. The same physical stimulus may, or may not, elicit an endogenous component, depending on several variables: the degree to which that stimulus is relevant to the task that the subject is performing, the attention the subject invests in the stimulus, and the extent to which the stimulus requires, or does not require, shifts in the subject's strategy. Such variables as the payoffs for task performance, the anticipated difficulty of the task, and the span of the short-term memory determine the amplitude, the latency, and the scalp distribution of the endogenous components. (For reviews of the endogenous components see Hillyard, Picton, & Regan, 1978; Donchin *et al.*, 1978; Tueting, 1978; Donchin, 1979).

The following endogenous components have been identified with some consistency. Components are labeled with letter-number combinations. The letter indicates the polarity of the component (negative or positive). The number represents the usual temporal interval, in

milliseconds, from the eliciting stimulus to the peak of the component (the "latency").

1. N100

This negative component is present in ERPs elicited by almost all stimuli of moderate and high intensity. While N100 has many of the attributes of exogenous components, recent evidence suggests that its amplitude is modulated by the degree to which the subject is selectively attending to the eliciting stimuli. Particularly well known is the work of Hillyard and his associates (Hillyard *et al.*, 1978). They presented stimuli at a high rate to each of the ears, or at different loci in space. Such physical cues were assumed to define input "channels." The subject was instructed to process stimuli that arrived in one channel and to ignore the input to other channels. The N100 elicited by stimuli in the attended channel was larger than the N100 elicited by the unattended stimuli. It now appears that the amplitude of N100 varies because Nd, a negative component that coincides in time with N100, is affected by attention (Naatanen & Michie, 1979).

2. N200

This ERP component is elicited whenever a rare or unexpected event occurs. It is of particular interest because it covaries on a trial-to-trial basis with reaction time (Ritter, Simson, Vaughan, & Friedman, 1979; Renault & Lesevre, 1979) and becomes longer in latency in conventional ERP averages when target stimuli are made more difficult to discriminate from nontarget stimuli (Goodin, Squires, Henderson, & Starr, 1978; Towey, Rist, Hakerem, & Sutton, 1980; Naatanen, Hukkanen, & Jarvilehto, 1980). In all of the studies cited, changes in the latency of N200 were accompanied by roughly equivalent changes in the latency of the P300 component to be discussed below. The significance of N200 has been overlooked until recently because this endogenous component is often obscured by exogenous components that occur in a similar time region. The most direct examination of N200 occurs when subjects perform a task with respect to infrequent, random omissions in a train of stimuli delivered at a constant rate of about one stimulus per second. The stimulus omissions elicit an N200, in the absence of any exogenous potentials, followed by a P300. However, subtraction procedures have been successfully used to remove overlapping exogenous components

to uncover N200 elicited by physically present target stimuli. The N200 component has been shown to be modality-specific in its scalp distribution for auditory and visual stimuli (Simson, Vaughan, & Ritter, 1976, 1977) and is generally regarded as being related to the process of discrimination.

3. P300

This is a large-amplitude, endogenous component reliably recorded in association with task-relevant, unexpected stimuli. It will be discussed in detail in Section IV.

4. *Response-Preceding Negative Waves*

The contingent negative variation (CNV) and the readiness potential (RP) are both clearly endogenous. These two components, antecedent to an event, apparently represent anticipatory processes. The RP, discovered by Kornhuber and his associates in Germany (Kornhuber & Deecke, 1965), is a slow negative potential that appears up to 800 msec prior to the execution of a response (see Kutas & Donchin, 1977, for a review). It gradually increases in amplitude and peaks just prior to the response, then shifts to a rapid change in the positive direction. The RP tends to be larger over the hemisphere contralateral to the responding hand. Its onset depends on the point in time at which the choice between the responding hands is made. The CNV is a similar component that appears when one stimulus heralds the arrival of a second, imperative stimulus to which the subject must respond. Again, a slow negative potential emerges some 400 msec following the warning stimulus and gradually increases to a peak just prior to the imperative stimulus. While the CNV can be recorded reliably, it has been somewhat difficult to interpret, as its amplitude and waveform are sensitive to many different variables.

Attempts to assess the joint variance of consciousness and ERPs have taken a number of forms, which may, for convenience, be classified in three categories. These are attempts to distinguish between brain responses to supra- and subliminal stimuli, to relate aspects of the ERP to the contents of consciousness, and to relate ERPs to human information-processing. In the following sections, we review these approaches to the psychobiology of consciousness. Our intent is not an exhaustive review of the literature. Rather, we shall illustrate in each case the approach and the methodological and conceptual problems it encounters by focusing on a few typical studies.

II. ERPs, THRESHOLD, AND SUBLIMINAL PERCEPTION

Consideration of the relationship between ERPs and behavioral measures of stimulus detection or threshold provides a useful starting point for our discussion of ERPs and consciousness. Are there measurable differences in ERPs to stimuli that are above the threshold for conscious perception as compared with those elicited by stimuli presented below this threshold? Indeed, do stimuli presented below this threshold for consciousness evoke any brain activity?

Experiments designed to answer these questions have come from many quarters and from a variety of interests. In many clinical settings, the ERP is used as an objective measure of sensory threshold that is independent of the need for overt responses. Witness, for example, the use of ERPs in audiometry (Picton, Woods, Baribeau-Braun, & Healy, 1977). To determine if the auditory system is intact, the audiologist must first determine if a patient "can hear." When direct questions cannot be addressed to a patient, the audiologist may utilize ERP measures. It is important, in this context, to determine what can be inferred about a patient's awareness of a tone from the obtained ERPs. A similar interest in threshold measurements comes from the psychophysicist, who may be interested in the degree to which ERPs manifest the various relationships that have been established between the physical parameters of stimulation and the subjective judgments of sensation (see Hillyard *et al.*, 1978, for a discussion of these relationships). Investigators who have conducted studies relating ERPs to threshold measures have been motivated by an interest in the phenomena of subliminal perception. In these studies, ERPs have been used to validate, or test, the claim that stimuli too weak in energy, or too short in duration, for conscious perception can nevertheless influence behavior. These studies of ERPs for threshold and subthreshold are most germane to our present discussion; a brief review of this literature follows.

A few general remarks are in order. In all of the studies of threshold and ERPs, the investigators examine the relationship between subjective reports of stimulus detection and measures of the ERP. Although these experiments may seem to be straightforward, they are fraught with methodological difficulties. The problems encountered in such studies have been discussed by Donchin and Sutton (1970), Regan (1972), and Sutton (1969).

The concept of *sensory threshold*, in the sense of an absolute limit for conscious perception, has proved inadequate to account for the human's performance as a signal detector. The task assigned in "threshold" or signal-detection studies is more conveniently modeled as a decision task. Whether any given stimulus will be "detected" depends not

only on a subject's sensitivity to the stimulus but also on the subject's criterion for stimulus detection. This criterion (labeled *response bias* in the signal-detection literature; Green & Swets, 1977) is affected by the relative probability of a signal as well as by the perceived payoffs and costs associated with correct and incorrect decisions. The "threshold," then, is a statistical abstraction rather than a physical entity in the sensory system. The decision mechanisms control the subject's behavior whether or not they are explicitly addressed in the experimental design. Thus, experiments that ignore the distinction between sensitivity and criterion are suspect.

The measurement of the ERP presents additional problems for the threshold paradigm. The ERPs must be extracted from the larger-amplitude "background" EEG activity. The purity of the extraction depends on the relative amplitude of the EEG and the ERP. The extraction process is also affected by the degree to which the ERPs are synchronized with the eliciting event. Low-intensity ("liminal") stimuli evoke minuscule and poorly synchronized ERPs, which are, therefore, difficult to extract. This problem is compounded in scalp recordings as the scalp attenuates ERP amplitudes and distorts the relative contributions from near and distant neural sources (Goff, Allison, & Vaughan, 1978).

Additional problems arise when investigators ignore the componential nature of the ERP. Much of current ERP research is concerned with elucidating the "vocabulary" of ERP components and identifying which physical and psychological manipulations control the variance of particular ERP components (see Callaway *et al.*, 1978; Otto, 1978). As we have noted, different components are affected in different ways by experimental manipulations. It is therefore quite inappropriate to discuss the effects of variables on "the" ERP. Studies that have treated the ERP waveform as a unitary entity, ignoring the detailed structure of the waveform, are of limited value. Lastly, given the trial-by-trial changes evident in detection behavior, it is necessary to record behavioral and ERP measures simultaneously and to sort the ERP trials on the basis of behavioral outcome. These considerations should be borne in mind as we proceed to discuss some of the attempts to relate ERPs to the detections of weak stimuli.

Shagass and Schwartz (1961) reported that an ERP appeared at the scalp whenever the eliciting stimulus exceeded the threshold for conscious awareness. Schwartz and Shagass (1961) extended their work by recording directly from the cortex of cats while simultaneously recording from thalamus and peripheral nerve. They found that shocks of an intensity sufficient to evoke a response in the peripheral nerve also evoked responses at the thalamus and cortex. The authors concluded from these two studies that there was no physiological substrate for

subliminal perception: all stimuli that excited the peripheral receptor evoked a cortical response (in the cat), and all stimuli that evoked a cortical response could be consciously perceived (in the human).

The conclusions of Schwartz and Shagass were supported by Domino, Matsuoka, Waltz, and Cooper (1964), who recorded somatosensory ERPs simultaneously from the scalp and the epidural surface of the cortex. These investigators reported that the ERP became identifiable at threshold levels. Unfortunately, no information was provided regarding how the thresholds were determined or whether an attempt was made to record ERPs elicited by subthreshold stimuli.

Another attempt to relate ERPs to subliminal perception was made by Shevrin and Fritzler (1968; see also Shevrin, Smith, & Fritzler, 1969), who reported that a positive component at 175–275 msec latency, recorded from a frontal-occipital bipolar derivation, discriminated between two stimuli presented at subliminal durations. The stimuli consisted of a rebus figure composed of a pen and a knee and an abstract figure matched with the rebus figure for size, color, general configuration, and brightness but devoid of complex internal contours and specific content. These stimuli were presented in blocks for durations of 1 msec, 30 msec, and then 1 msec again. There were 60 stimulus presentations in each exposure block; after each 10 stimuli (5 rebus and 5 abstract), the subjects were asked to describe what they saw and then free-associate for 2 min. These free associations were the behavioral data; they were scored in three categories for their relationship to the rebus figure.

Libet, Alberts, Wright, and Feinstein (1967, 1972; see also Libet, 1965, 1966; Libet, Alberts, Wright, Lewis, & Feinstein, 1972; Libet, Alberts, Wright, Delattre, Levin, & Feinstein, 1964) examined ERPs to stimuli whose intensity was either above or below the threshold for conscious perception. Libet *et al.* (1967) reported that the difference between perceived and unperceived stimuli was manifested by both qualitative and quantitative differences in the ERP. Recording directly from the pia–arachnoid surface of the postcentral gyrus, Libet *et al.* found that stimuli that were below the threshold for conscious perception did elicit an ERP. These ERPs were smaller than those elicited by suprathreshold stimuli. Furthermore, only the early (“primary”) ERP components were elicited by the “unconscious” stimuli. Libet *et al.* attributed the difference between their results and those mentioned above to the greater resolution afforded by recording directly from the cortex. In fact, their scalp and epidural recordings did not reveal these subthreshold ERPs. In contrast to Schwartz and Shagass (1961), Libet *et al.* claimed that their data indicate a possible physiological basis for subliminal perception: the nervous system responds to stimuli that are not consciously perceived. Presumably, stimuli invoke activity that is

available for unconscious processing; Libet (1965, 1966, 1973) has elaborated a theory of unconscious and conscious processing of stimuli based on these results and other data relating to direct cortical stimulation.

While certainly intriguing, Libet *et al.*'s (1967) data, as well as the data reported by Shagass and Schwartz (1961), are somewhat difficult to interpret (Donchin & Sutton, 1970; Sutton, 1969). Particularly troubling is the manner in which the subject's "threshold" was assessed. Libet *et al.*'s subjects were instructed to attend for possible presentations of stimuli and to report if they had *consciously* perceived, or had not perceived, the stimuli. They were also allowed to report that they were "uncertain" whether a stimulus had been presented. Libet (1965, 1966, 1973) was explicitly critical of the forced-choice measures of threshold prevalent in contemporary psychophysics as methods for assessing subjective experience. He apparently feels that the subject may be able to respond manually to the presentation of a stimulus without, in fact, consciously perceiving that stimulus. However, the fact that Libet's subjects made a very small number of "false alarms" suggests that the subjects adopted a strict response criterion. It is conceivable, therefore, that with a more relaxed response criterion, subjects would have "detected" some portion of the subliminal stimuli. Libet, to be fair, insisted that he was measuring something quite different from what one tries to measure by employing signal-detection procedures. Libet was interested in "subjective experience," not in "detection." Subjective experience was defined by him to be whatever causes a subject to report that she or he "feels" the stimulus. Thus, the subject's reports are the "primary"—and according to Libet, the only—data on subjective experience. Yet, the evidence is overwhelming that an individual's report on subjective experience, whether spoken or otherwise communicated, is determined by both "sensitivity" and "criterion" (Green & Swets, 1977). It is therefore difficult to interpret data that ignore this distinction.

The studies reviewed in the preceding paragraphs attempted to determine if a physiological substrate exists for subliminal perception. To this effect, the investigators tried to ascertain if ERPs can be elicited by stimuli presumed to be below the "threshold" of consciousness. Other investigators have considered ERPs and the sensory threshold for quite a different purpose. Their intent has been to evaluate the validity of the claim that the ERP is a "correlate" of psychological processes. Their testing has been based on the assumption that any supraliminal stimulus must elicit an evoked potential. Further, they have assumed that the absence of ERPs after a supraliminal stimulus indicates that ERPs are not useful as correlates of information processing, or as measures of perception or sensation.

Clark, Butler, and Rosner (1969) made this latter argument as they observed a dissociation between sensation and ERPs. They recorded ERPs from seven male subjects who were anesthetized to different depths, through the inhalation of different concentrations of cyclopropane. The subjects' thresholds for the perception of mild electric shocks at the right ulnar nerve were determined by the descending method of limits prior to inhalation of the drug. Each subject indicated whether he had perceived the shock by pressing a button with his left hand. After threshold was determined in this manner, the subjects were administered the anesthetic.

The subjects' sensory thresholds were assessed for each concentration of cyclopropane. The ERPs elicited by stimuli presumed to be supra- and subliminal were also recorded at each level of anesthesia. However, the psychophysical and the electrophysiological data were recorded on separate occasions, under somewhat different circumstances. In general, the amplitude of the ERPs diminished with deepening levels of anesthesia and, in three subjects, disappeared altogether at the time that the high concentrations of the anesthetic were administered. The sensory thresholds increased slightly during the anesthetic sessions. Of particular importance, according to Clark *et al.* (1969), was the finding that some stimuli that were definitely supraliminal (that is, those of which the subjects were presumably "conscious") failed to elicit any ERP. On the basis of these data, the authors asserted that, at best, the ERPs are unnecessary for at least some sensory experiences. Clark *et al.* suggested that the evoked potential may be "full of sound and fury signifying nothing" and may play "no essential or important role" in determining perceptual reactions to those parameters that might be encoded.

Donchin and Sutton (1970) found Clark *et al.*'s study wanting on many grounds. A particularly important weakness in Clark *et al.*'s study was that it measured the subject's sensory threshold using a technique that ignored the subject's decision criterion. Thus, it was quite possible for the subjects to use different decision criteria when in different levels of anesthesia. If the subjects relaxed their criterion with increasing levels of the drug, then the number of correct detections might not change, although the number of false positives (values not obtained with the procedure of Clark *et al.*, 1969) would also increase.

Another serious weakness in the study by Clark *et al.* is that they obtained the ERPs on different occasions than were used to measure the sensory threshold. The procedures used during threshold measurements were designed to focus the subjects' attention on the stimuli. The procedures used when the ERPs were recorded did not prod the subject to be attentive. Thus, the behavioral and the electrophysiological

data were recorded while the subjects were in quite different attentional states. It is well known that attentional state plays a major role in determining the amplitude and the latency of ERPs (Haider, Spong, & Lindsay, 1964). It should also be noted that the disappearance of ERPs from scalp recordings does not eliminate the possibility that ERPs are present but are too small in amplitude to be measured without recording from inside the cranium.

A number of experiments have since been performed to clarify the relationship between ERP components and threshold-level stimuli in the context of the theory of signal detection (Hillyard, Squires, Bauer, & Lindsay, 1971; Paul & Sutton, 1972, 1973; Squires, Hillyard, & Lindsay, 1973; Squires, Squires, & Hillyard, 1975; Squires, Squires, & Hillyard, 1975). Hillyard *et al.* (1971) established that the amplitude of the P300 component of the ERP bore a systematic positive relationship to the subject's auditory "sensitivity" (the d' of signal-detection theory). Furthermore, Hillyard *et al.* (1971) established that while P300s were reliably elicited by detected threshold-level stimuli in the signal-detection task, no visible ERPs were elicited by stimuli of the same intensity when the subjects were not actively attending to the stimuli.

Paul and Sutton (1972, 1973) examined the relationship between response criterion and ERP components in an auditory signal-detection paradigm. In their studies, criterion was manipulated by varying the monetary value of correct responses and the penalties for false positives. Paul and Sutton also varied the probability that the signal would be present on any trial. Their results indicated that the amplitude of the P300 component increased with the increasing strictness of the subjects' criterion, no matter what caused the criterion to vary. Both Hillyard *et al.* (1971) and Paul and Sutton (1972, 1973) have interpreted their data in terms of the subject's confidence. The more confident the subject is in the detection of the signal, the larger the amplitude of P300.

The relationship of confidence to P300 amplitude in the signal-detection paradigm was studied in a series of papers by Squires and his colleagues (K. Squires *et al.*, 1973, 1975; N. Squires *et al.*, 1975). Using a cue light to synchronize the ERP to the presence or absence of an auditory signal, Squires was able to demonstrate that the amplitude of P300 was equal in both correct and incorrect signal-present decisions. Large P300s could also be elicited to high-confidence correct rejections, but only when these signal-absent decisions were relatively infrequent.

Thus, it seems that the P300 varies systematically with the nature of the subjects' decisions in a task of detecting threshold-level stimuli. This systematic variation is best seen when appropriate behavioral measures are taken and the ERP data and overt responses are obtained simultaneously and sorted on the basis of the subjects' decisions. It makes

little sense in this context to inquire if supraliminal stimuli do or do not evoke an ERP. Whether they do depends on the processing activities invoked by the stimuli as the system goes about the business of deciding whether to report a detection. The subject's report is a product of the processes affecting the sensitivity and the response bias on any trial. The ERPs reflect some of these processes. In fact, different ERP components reflect different processes. Thus, it is not particularly meaningful to ask, as Clark *et al.* (1969) did, if ERPs in general are related, under poorly specified conditions, to the sensory "threshold." The studies conducted within the framework of signal-detection theory by Hillyard, Sutton, and their associates have been more fruitful.

In general, the ERP data and threshold data generated by Clark *et al.* (1969) are in agreement: ERP amplitudes diminish and thresholds increase as the level of anesthesia deepens. Clark *et al.* erred in expecting behaviorally determined thresholds to covary in a one-to-one manner with their physiological measures. Clark *et al.*'s conclusions were based on the implicit assumption that the brain processes manifested by the ERP components must be identical to a behavioral product: a button press. This assumption is not valid. Although some ERP measures appear to be related to parameters of sensations, these relationships are often nonlinear (Hillyard *et al.*, 1978). Of particular note is the tendency of the ERP components to saturate—that is, to reach maximum amplitude—before behavioral measures of sensation asymptote.

The studies reviewed in this section have established that stimuli that subjects deny perceiving sometimes elicit an ERP. Even when the ERPs are elicited by subthreshold stimuli, they tend to be restricted to early components. Whether one accepts these data as relevant to the issue of subliminal perception depends on one's point of view. Libet is essentially Titchnerian. He accepts the subjects' introspections as veridical descriptions of experience. If one accepts this view, then Libet's data are indeed fascinating. A particularly striking aspect of these data is that the difference between the ERPs elicited by conscious and unconscious stimuli is that the conscious stimuli elicit both early and late components, whereas only early components are elicited by the unconscious stimuli. These data are consistent with the view of the early components as "specific" and the late components as "nonspecific," but crucial for conscious perception (Hernandez-Peon, Scherrer, & Jouvet, 1956; Lindsley & Wicke, 1974).

It must be recalled, however, that this distinction does not hold up well under close scrutiny. Williamson, Goff, and Allison (1970) were able, for example, to show that the so-called primary vertex potential is quite diffuse. Vaughan (1974) and his associates have, on the other hand, presented data supporting the "specificity" of this wave. Fur-

thermore, the structure and the functional significance of the reticular function have proved quite a bit more complex than presumed by the early models. Libet's data provided a very useful framework for elucidating this problem. Regrettably, his Titchnerian orientation makes it difficult to use his data. Much as Libet disagrees, the evidence is strong that individuals' reports in a detection task are subject to response bias. As the bias was not measured by Libet, it is not possible to know if the changes he observed were changes in sensitivity or in response bias. Until such data are available, this unique source of information on consciousness and ERPs has not fulfilled its promise. While we are not convinced by Libet's interpretation of his data, we do not deny the value of the paradigm he adopted. There is a point in recording, and analyzing, ERPs within the context of the signal-detection experiment. Libet's opportunity to do so, during surgery, from the exposed cortex is enviable.

What should be noted, we think, in designing such experiments, is the distinction we have made between process and product. The overt report that a subject makes on a given trial is the final product of a complex of interacting processes. These may include the activity in the sensory systems, leading from receptor to cortex, as well as the confluence of heuristic, motivational processes, the demands of concurrent tasks, and the changing strategies that the subjects adopt to deal with their environment. The ERPs measured in response to the stimulus may reflect any of these processes; therefore, the relation of the ERPs to the final product may depend on the extent to which this process affects the variance in this product. It is for this reason that one cannot declare the ERP to be, or not to be, "related" to the subject's overt report without considering the total complex of the factors that determine this report.

III. THE CONTENTS OF CONSCIOUSNESS AND ERPs

In the previous section, we discussed the extent to which the presence of an ERP component reflected a person's conscious awareness of the evoking stimulus, and we found the results equivocal. The investigators whose work is reviewed in this section have focused on supraliminal stimuli. Their basic assumption has been that specific aspects of conscious experience are reflected in the ERP. Studies designed to obtain such correlations generally take one of two forms. One version tests the hypothesis that the same physical stimulus presented on different occasions may lead to different percepts and that the ERPs recorded in association with the different percepts will be different. The difference in the ERPs is then attributed to the differential meaning

ascribed to the stimulus. Such studies generally analyze the ERPs elicited by the same physical stimulus when endowed, naturally or by the experimenter, with different meanings.

Several experimenters presented the same physical stimulus in different contexts in order to test the hypothesis that the form of the ERP would vary with percept (Thatcher, 1977; Johnston & Chesney, 1974; Sandler & Schwartz, 1971; Brown, Marsh, & Smith, 1976; Teyler, Harrison, Roemer, & Thompson, 1973). Sandler and Schwartz (1971) employed ambiguous figures, thereby changing content but not the physical characteristics of the stimuli. They noted small waveform differences in the occipital ERPs, depending on which of the percepts was dominant. There were, however, major difficulties with the experiment (recognized by the authors) that restrict interpretation of the results. The stimulus they used was the "gypsy girl" ambiguous figure. It is generally the case that there is a bias about which figure is seen on initial presentation of the figure. As the male figure turned out to be dominant, the subjects reported difficulty in maintaining a perceptual set (of the alternate percept) during the ERP recording. In addition, there were no controls over attentional factors, which have been shown to have profound effects on ERP waveforms (Hillyard *et al.*, 1978).

Johnston and Chesney (1974) used a very similar approach. They presented an ambiguous figure that could be identified either as the letter *B* or the number *13*, depending on context. They reported, on the basis of a principal-component analysis of the waveforms, that the ERPs to the ambiguous stimulus differed, depending on whether it was perceived as a number or a letter. Because of the localization of the effect to the frontal electrode sites, they concluded that the visual cortex was more involved in the representation of the physical characteristics of stimuli, whereas the frontal areas were more concerned with the representation of meaning. The study has been criticized (Galbraith & Gliddon, 1975) on the grounds that the subjects' task was to say what they saw as quickly as possible after seeing it. This requirement could easily have led to a confounding of the stimulus ERP with vocalization potentials, both neural and muscular. The differences between the frontal and occipital recordings cannot be assessed from the data presented, as concurrent recording from both sides was accomplished in one subject only. Furthermore, as in Sandler and Schwartz's (1971) study, there is a tendency to perceive the ambiguous figure, when presented out of context, as the letter *B* rather than as the number *13*. As Johnston and Chesney used fairly short presentation intervals, it is possible that they avoided this bias.

Yet another problem with this study is that it lacked a very important control. Consider Johnston and Chesney's claim that the am-

ambiguous stimuli elicit different ERPs when perceived as *B* or *13*. If there is, as they claimed, a difference between the ERP associated with the perception of a number and the ERP associated with a letter after the presentation of ambiguous stimuli, they should have established their point by showing that the ERPs to a class of unambiguous numbers is distinct from the ERPs elicited by a class of unambiguous letters. Furthermore, the ERP elicited by the figure when perceived as *B* should be more "lettery" than "numbery." Without these data, it is not possible to tell if the effect is due to unspecified interactions within the contexts or is indeed due to the manner in which the brain responds to numbers or letters.

A similar study in which meaning was determined by the linguistic context in which stimuli were presented was carried out by Brown *et al.* (1973, 1976) and Teyler *et al.* (1973). These studies were designed to assess hemispheric utilization induced by stimuli requiring linguistic analysis, yet they do bear on the issues at hand. Teyler *et al.* (1973) reported that different ERPs were elicited by clicks associated with ambiguous words, depending on whether the subject was thinking about the noun or the verb meaning of the word. Brown *et al.* reported a similar study, in which they recorded ERPs elicited by words rather than by clicks. They found that the ERPs elicited by the word *fire* in the phrases "sit by the fire" and "ready, aim, fire," were different, whereas the ERPs elicited by the same word in the phrases "fire the gun" and "fire is hot" were quite similar, because at the time the word *fire* was presented, the subjects could not tell if it served as a noun or a verb. These differences in the brain's response to the word *fire* in different contexts appeared only in recordings from electrodes placed over the "speech" areas in the left hemisphere. On the basis of such results, Brown *et al.* (1973) concluded that "context-produced differences in the meaning of a word" produced systematic differences in the waveform of the ERP. Not enough of the data are presented, so the differences in waveform cannot be evaluated with certainty. There are also some problems in the analysis used (see Friedman, Simson, Ritter, & Rapin, 1975; Donchin, Kutas, & McCarthy, 1977, for criticism). Subsequent work by this group (Brown *et al.*, 1976) extended the analysis and the range of data considered. It appears now that there are differences between ERPs elicited by words presented at the beginnings and at the ends of the sentences. However, these differences are somewhat hard to interpret in terms of specific components of the ERP, as the entire ERP waveform seems to disappear. In a subsequent report, Marsh and Brown (1977) described a principal-component analysis of their data. They reported effects of "meaning" on three different components. Such analyses, if pursued, will be of considerable value.

Not all such studies have reported positive results. There have been reports that decisions about the meaning of stimuli can occur without concomitant changes in the ERP. Rem and Schwartz (1976) recorded ERPs elicited by anaglyph versions of Julesz patterns. They recorded ERPs from occipital-parietal and vertex-mastoid sites that were elicited by a square imposed on a textured ground, a T-shape on a background, and a figureless textured area. They varied exposure durations and used different-colored filters. They reported that the ERP waveforms were sensitive to the microstructure of the Julesz patterns and were affected by the color and depth cues in the figures. They found, however, no differences between the ERP waveforms that could be attributed to the figural content of the stimuli.

When successful, the above studies share the claim that if the same physical stimulus is presented in different contexts that cause it to be perceived differently, it will elicit different ERPs. A much stronger statement of this position has been derived from the assumption that unique ERP waveforms reflect the specific perception elicited by specific stimuli. In its extreme version, this view can lead to the assertion that there is a unique ERP for Grandma's red Volkswagen. As stated by Sandler and Schwartz (1971), "Taken to their logical conclusion, our findings suggest that every percept amenable to study by ER methodology should have its individual electrophysiological code." The original attempt to search for such a close correspondence between stimulus content and the ERP was made by John, Herrington, and Sutton (1967), who compared ERPs to square, diamond, words, etc. They reported that (1) the ERPs elicited by a blank flash differed from those elicited when a geometric form or word was present in the visual field; (2) different shapes of equal area evoked different ERPs; (3) similar shapes of different area evoked similar responses; and (4) different words, equated for area, elicited different ERPs. The study, however, is not convincing. The differences reported were slight and difficult to see. Only 60% of the subjects showed any systematic effects. There was a great deal of inter- and intrasubject variability. The subjects were not assigned a task that required that they differentiate stimuli according to their meaning. Further, there are ample data confirming the role of the size, and the shape, of stimuli in determining ERP waveforms. The effects of "meaning" can probably be attributed to the fact that different retinal elements were stimulated by the different visual stimuli.

There have been several attempts at partial replication of the John *et al.* (1967) study (e.g., Purves, Low, & Baker, 1979; Purves & Low, 1978). In particular, a replication by Gringberg-Zylberbaum and John (unpublished, referenced in John & Schwartz, 1978), included controls intended to deflect some of the criticisms of John *et al.* (1967). John and

Schwartz felt that the new data supported the early conclusions that stimulus content is encoded in the waveform of the ERP. Further, Gringberg-Zylberbaum and John found that the differences observed in ERPs were particularly evident in certain brain regions in a manner consistent with the presumed functional anatomy of the brain: differences in letter size were represented in ERPs recorded over the occipital area, whereas the differences in meaning were observed in ERPs recorded over the parietal and temporal lobes.

From studies of differential generalization in cats, John (1967) has concluded that stimulus meaning is encoded by the wave morphology of the ERP. John reported that the ERP after response to a novel stimulus closely resembles the ERP usually caused by the stimulus to which the animal has learned to respond in the same manner. From work reviewed in detail elsewhere, John (1972) concluded that when the same physical stimulus has different meanings, the difference is reflected in the shape of the EP: "Waveshape of the EPs elicited by a neutral test stimulus in a differential generalization paradigm actually reflects readout of memory about specific stimulus-response contingencies."

Studies analogous to John's work with cats have been reported by Begleiter and his associates using human subjects (Begleiter, Porjesz, Yerre, & Kissin, 1973; Porjesz & Begleiter, 1975; Begleiter & Porjesz, 1975). They designed their experiments to show that "certain aspects of the EP reflect previous experiences of the organism . . . activation of memory traces . . . released from memory rather than evoked." Begleiter *et al.* (1973) used a warning stimulus to inform the subject of the intensity (low, medium, or high) of the following flash; in some instances, however, the flash presented was either brighter or dimmer than indicated to the subject. Thus, the authors could compare the ERPs elicited by the same physical stimulus following different cues. They found that the ERP waveform was determined by the expected intensity of the flash, rather than by the intensity of the flash actually presented. When a stimulus of medium intensity was preceded by a signal indicating that a bright flash would be presented, the resulting ERP was more similar to the ERP evoked by bright flashes (the cued stimulus) than by medium flashes (the actual stimulus presented). Similar results were obtained even when the subject predicted which intensity would be used on the next trial, or when the subject detected the intensity by pressing one of two appropriate buttons. In both cases, the expected intensity was reported to have a profound effect on the perception of the flash. The amplitudes of the N100-P200 components of the ERP elicited by the same physical stimulus were significantly different, depending on whether the subject predicted a bright or a dim flash.

Begleiter and his colleagues have reported success in replicating these results with several groups of subjects, under slightly different

experimental setups (Begleiter & Platz, 1969, 1971). Their interpretation of the data presents some problems. The waveforms associated with the medium-intensity flashes are indeed somewhat different, depending on the expected intensity. However, this difference is slight in comparison with the difference between ERPs associated with bright or dim flashes. Furthermore, inspection of the waveforms presented in the papers (see, for example, p. 154 in Porjesz & Begleiter, 1975) indicates that the ERPs evoked by the medium flashes are more similar to each other than to either of the ERPs elicited by the bright or the dim flash. Begleiter *et al.*'s techniques are insufficiently sensitive to allow confident acceptance of their interpretation. It would have been of interest to know if a pattern recognition procedure applied to the ERPs elicited by the medium-intensity flashes had indeed classified them as predicted by Begleiter's theory.

John and Begleiter have maintained that their results demonstrate that ERP waveforms represent a neural readout from memory. Such claims are based on their findings, in the paradigm described above, that different ERP waveforms can be elicited by the same physical stimulus, depending on the "meaning" or "significance" attributed to the event. However, even if one accepts their empirical assertion about the ERP waveforms, one need not conclude that the ERP waveform encodes the *content* of consciousness. Alternative explanations can be invoked for the similarity between the ERPs elicited by a novel stimulus and the ERPs elicited by the test stimuli.

For example, the similarity of the ERP waveforms to the test and novel stimuli may be due to the similarity in the manner in which they are processed, rather than to the fact that the two stimuli evoke the same percept. That is, stimuli may share some attributes (defined by the subject or the experimenter) that lead to similar processing activities. It may be this equivalence in the processing strategy employed in dealing with the various stimuli that is reflected in the ERP waveform. As shown in the next section, there is an abundance of data showing that many physically dissimilar stimuli elicit ERPs with similar waveforms as long as the stimuli are considered identical or equivalent *in terms of the subject's task*. John's and Begleiter's results, viewed within this framework, are in accord with those reviewed below, demonstrating the importance of expectancy, stimulus significance, and other task variables in determining the waveform of the late components of the ERP.

IV. THE ERP AND INFORMATION PROCESSING

The studies reviewed in the previous two sections attempted to establish a correlation between attributes of the ERP and specific be-

havioral products. In virtually all cases, the investigators were trying to demonstrate a correlation between aspects of the subject's performance and electrophysiological measures. Behavior, however, is almost always the terminal product of a variety of converging processes. An investigator may determine if a subject reports "awareness" of a stimulus or reports a stimulus to be bright or to be triangular or square. In each of these examples the "behavioral" measure that supplies the variable that enters into the correlation computation is a consequence of attentional, perceptual, and cognitive processes invoked by the joint demands of external inputs, the instructions to the subject, and the subject's past history. These are correlated with measures of some attribute of the ERP. The resulting correlation is considered a correlation between "behavior" and ERPs. A positive, or negative, correlation is presumed to indicate that the ERP is a "correlate" of the behavior. When the correlations are weak, difficult to replicate, and therefore hard to interpret, one questions the degree to which the ERP is indeed a proper "correlate" of behavior (Uttal, 1973).

The inevitable weakness of the correlations may become clear if due attention is paid to the important distinction between *products* and *processes*. The studies we have reviewed attempt to correlate the properties of a product with attributes of a subset of the processes that have produced it. As usual, when comparing apples with pears, the results are confusing. The subject's report that "a stimulus is bright" is the terminal point of the following processing activities, at least. The pattern of stimulus energy impinging on the receptors must be transduced and conveyed via the sensory nerves through the geniculate relay to the more central nodes of the cortical processing system. The stimulus must be identified and its level of energy determined and compared with stored information about brightness levels. This comparison is required if the system is to determine the absolute, or the relative, brightness of the stimulus. The outcome of that determination is somehow translated into an appropriate overt response. This process involves control of the musculature, selection of the appropriate verbal or motor components, and their emission. In turn, this process leads, perhaps, to the deposition in memory of the consequences of this particular interaction between the environment and the subject and the determination of its implications in the contents of memory relevant to the task that the subject is performing. Thus, the specific response "The stimulus is bright," emitted on a specific occasion, is a product that depends on the course of these different processes and on their interactions.

If we monitor one, or a few, of the component processes, we cannot expect a strong deterministic relationship between the monitored process and the final product. The final product is affected, to a larger or

smaller extent, by processes we do not monitor that succeed or accompany the process we do monitor, and by the interaction between the monitored process and the other processes. The degree to which any given process affects the final product varies with the circumstances. Sometimes, a process is strongly related to the product; on other occasions it is minimally related to the product. In general, the correlation between the process and the product depends on the share of the product's variance that is explained by the process's variance. It is often not possible to predict this share in advance.

The attempt to hang theoretical conclusions on the correlation between the ERPs and behavioral measures is doomed to fail if one ignores the need to consider other processes that contribute to the product's variance. In the present section, we illustrate this point by considering the P300 component of the ERP. This component is a manifestation, at the scalp, of neural activity that is intimately related to important stages in human information-processing activities (Donchin *et al.*, 1978). We shall try to show that the distinction between product and process is crucial to an understanding of the observed correlation between P300 and "behavioral" measures.

Specifically, we shall show that uninterpretable results are obtained when one attempts to relate the amplitude, latency, or scalp distribution of the P300 to specific behavioral products, disregarding the circumstances under which the observations are made. On the other hand, when the psychological terrain over which the information-processing system is traveling is taken into consideration, the data on the P300 fall into a coherent pattern (McCarthy & Donchin, 1978, 1979). We also examine here the degree to which information about the P300 enhances our understanding of the relationship between performance and consciousness. It will turn out that the important cognitive processes manifested by P300 are not necessarily conscious processes, even though the elicitation of P300 does depend on the subject's conscious awareness of a distinction between stimuli. Thus, at one and the same time, the P300, looked at from different points of view, appears to be "related" and "unrelated" to consciousness. The implications of these considerations in relation to the psychophysiology of consciousness are considered in the following section.

The P300 component was discovered by Sutton and his co-workers (Sutton, Braren, Zubin, & John, 1965; Sutton, Tueting, Zubin, & John, 1967). They noted that stimuli that, as they put it, "reduce the subject's uncertainty" elicit an ERP characterized by a large positive-going peak, with a latency of approximately 300 msec measured from the eliciting stimulus. The results, published formally by Sutton *et al.* (1965), were remarkable. It was dramatically evident that the same physical stimulus,

presented to the same subject, under virtually identical physical circumstances, elicits quite different ERP waveforms when the stimulus is presented in different psychological circumstances. As Sutton *et al.* noted, the neural activity manifested by the P300 is clearly endogenous. That is to say, it is not an obligatory response to a stimulus but is induced, or invoked, in the nervous system by the demands imposed on the subject by the task. In the decade and a half since the discovery of the P300, considerable effort has been invested in an attempt to elucidate the behavior and the functional significance of this component. Detailed reviews of the literature have been published by Tueting (1978), Donchin *et al.* (1978), and Donchin (1979).

In the main, the evidence is strong that the P300 is elicited by task-relevant stimuli that are, in some sense, unexpected. The relationship between these two variables is illustrated in the study reported by Duncan-Johnson and Donchin (1977). These investigators utilized an experimental paradigm that has been used frequently in studies of P300. The subject is presented with a Bernoulli series of events and is required to make a differential response to each of the two events that can occur in the series. A Bernoulli series, it will be recalled, is a sequence of trials on each of which one of two events may occur. The probability of one of the events occurring is P and the probability of the other event is $(1 - P)$. In a Bernoulli series, the two probabilities are constant for all trials in the sequence and are independent of the serial position of the trial. The Bernoulli series used by Duncan-Johnson and Donchin were constructed from a high-pitched and a low-pitched tone. In each of the series, each of the tones occurred with the indicated probability. The subject was instructed to count the number of times that high-pitched tones occurred. The amplitude of the P300 elicited by the stimuli varied with the probability of the tones. The rarer the stimulus, the larger the P300 it elicited. This basic finding has, of course, been repeatedly reported (Tueting, Sutton, & Zubin, 1971; K. Squires *et al.*, 1975; Roth, Ford, Lewis, & Kopell, 1976).

Another important attribute of P300 can be seen by comparing ERPs elicited when the subject was instructed to count the tones with those elicited by the same tones when the subject was required to solve a word puzzle rather than to listen to the tones. Such "ignored" tones do not elicit a P300. Thus, the rarity of the tones is not a sufficient condition for the elicitation of P300. The tones must also be relevant in some sense to the subject's task (see Johnson & Donchin, 1978).

While these data suggest that it is the relative frequency of events in the series that affects the P300, much evidence has been developed that it is not the objective relative frequency of the stimulus that deter-

mines the P300 amplitude but the probability assigned to the stimulus by the subject (see Donchin, 1979). A detail of crucial importance is that the probabilities to be considered are not probabilities associated with specific *physical* events but the probabilities associated with the *categories* into which these events are classified by the subject's task. The Bernoulli series used to elicit the P300 must, by definition, constitute sequences of two events. However, these two events need not be unique physical stimuli. In fact, each event can be realized by one of many distinct physical stimuli as long as the subject's task, and the instructions to the subject, impose a dichotomy on this diversity of stimuli. Johnson and Donchin (1980), for example, have shown that when a series is constructed from *three* stimuli, one of which is to be counted and the others of which are to be ignored, the two uncounted stimuli are treated as if they belong to one category, that of the irrelevant events. Friedman *et al.* (1975) found a similar result for five stimuli, whether they consisted of five words or five nonverbal human sounds. Kutas, McCarthy, and Donchin (1977) have shown that the Bernoulli series could be constructed from many different words divided according to some semantic rule (e.g., synonyms of some word, or names of males vs. names of females). Courchesne, Courchesne, and Hillyard (1978) have shown that one can assemble Bernoulli series from two classes of letters distinguished only by the instructions given to the subject prior to the presentation. In work in progress by Towle and Donchin (in preparation), covers of *Time* and *Newsweek* were used and divided on different runs according to different categorization rules (for example, politicians vs. entertainers, male figures vs. female figures). The same physical stimulus did or did not elicit a P300, depending on the category to which it was assigned. The categories, of course, varied from one condition to another with the instructions to the subject.

It appears reasonable to suggest that the P300 is a manifestation, at the scalp, of neural action that is invoked whenever the need arises to update the "neuronal model" (Sokolov, 1969) that seems to underlie the ability of the nervous system to control behavior. We assume the existence of a mental model (or a world map, or an image, or a schema). This model is continually reviewed to determine action because inputs must be continually compared against this model to determine outcomes and the possibilities of various action consequences. The appearance of a discrepancy between inputs and the model has been defined by Sokolov as the event eliciting the orienting reflex. As a consequence of the recognition that a discrepancy occurred, the model may or may not be modified. The P300 may represent the updating of the model. Whether the model will be updated and the extent to which it will be updated

depends on the surprise value, and on the relevance, of the events (see Pribram & McGuinness, 1975; Donchin, 1975; McCarthy & Donchin, 1979; Stuss & Picton, 1978).

The corollary of this concept important to the present review is that P300 represents the activation of a component process in the scheme of information-processing activities. This process is activated in parallel with the specific actions that subjects may take on any given trial. This process has more to do with the establishment of neuronal models than with the active utilization of information on any given trial. The process is likely to begin at any point during a trial, to proceed for any length of time, and to terminate after unspecified intervals.

The dissociation between the overt behavioral products and the attributes of the processes that are manifested by P300 can be illustrated by an analysis of the latency of P300. It is immediately obvious, on perusing the literature, that the value 300, which appears in the component's label is a misnomer. The *minimal* latency with which P300 appears is in fact 300 msec. Very frequently, especially in experiments using "simple" stimuli, the latency is indeed 300 msec. Yet, there are numerous reports of P300 with latencies considerably longer than 300 msec. The label *P300* has been applied to positive-going peaks with a latency of 400, 500, and even 900 msec. Some investigators view peaks that appear with different latencies as representing different ERP components. But despite the diverse latencies of these peaks, they share most of the important attributes of P300. It is parsimonious to regard as instances of P300 all positive-going peaks whose scalp distribution is similar to that of the "classical" P300 (that is, those that are largest in the parietal electrode, smaller in central electrodes, and quite small in frontal electrodes), and which respond to experimental manipulations in the manner characteristic of P300.

The variable latency need not be puzzling if one recalls the endogenous nature of the P300. If the component is a manifestation at the scalp of cortical activity invoked by the need to update the neuronal model, then, unlike the exogenous components, whose latency is determined essentially by the time course of the primary activity elicited in relatively fixed sensory pathways and relays, the P300 depends on the activation of *internal* processes. As the elicitation of the P300 depends on the probability associated with the *category* into which the eliciting event is classified, the events must be fully categorized before the P300 can be elicited. Otherwise, the probability of the category could not be checked against the external model. This checking process involves, no doubt, contacts between sensory and memory processes and a fairly elaborate evaluation of strategies, purposes, and intentions. Therefore, one cannot expect the activity manifested by P300 to appear with a

relatively fixed latency following a stimulus. The latency of P300 varies naturally as a function of the time course of the many processes that must precede the elicitation of the P300 (for a more detailed discussion of this issue, see Donchin *et al.*, 1978).

The distinction between products and processes has proved quite important in disentangling the confusing pattern of the results that are obtained when the latency of an overt motor response to a stimulus (the "reaction time") is compared with the latency of the P300 elicited by that same stimulus. The overt response is, of course, the terminal product of a multiplicity of processes (Posner, 1978). The relationship between the variance of P300 latency and the variance of the reaction time depends on the circumstances of the experiment. The two measures will be correlated (that is, the variance in one will be fully accounted for by the variance in the other) if, and only if, the component process that leads to P300 is predominant in determining the latency of the motor response. This will not be so if the subsequent processes that determine the duration of the reaction interval are affected by factors that do not affect the P300 process. The reaction time and P300 latency will then be uncorrelated (that is, the variance in the reaction time could not be accounted for by the variance in P300).

Kutas *et al.* (1977), for example, have studied the relationship between P300 latency and reaction time in an experiment utilizing the odd-ball paradigm. A Bernoulli series, constructed from male or female names, was presented to a subject, the female names with a probability of .20. These rare names, as expected, elicited a large P300. An algorithm adopted from Woody (1967) was used to measure the latency of P300 on each trial of the experiment (Ruchkin & Sutton, 1978). The subjects performed the task under two different instructional regimes: accuracy was emphasized in one; speed, in the other. The correlation between reaction time and P300 was found to be significantly different from zero when the subjects were trying to be accurate. Not so when they were trying to be fast; in that case, small, insignificant correlations were observed between reaction time and P300 latency. When subjects are trying to be accurate, their P300 and reaction time processes are more tightly coupled than when the subjects try to be fast. It is as if the response during the accuracy conditions is contingent on the results of the processing that ultimately lead to the P300. In the speed condition, the process associated with the P300 appears to be decoupled from the processes that ultimately lead to the reaction.

McCarthy and Donchin (1981) have provided a confirmation of our postulate that P300 latency is proportional to stimulus evaluation processes and is relatively independent of response selection processes. Subjects were presented on each trial the word *right* or the word *left*.

These were embedded either in a matrix of other characters, randomly selected, or in a matrix of # signs. A cue word preceding these matrices indicated to the subject whether to make a compatible or an incompatible response to the stimulus. When a compatible response was called for, the subjects responded to the word *right* by pressing a button with the right thumb, and to *left* with the left thumb. Incompatible response called for pressing the left button with the left thumb when the stimulus was *right*, and vice versa for the command *left*. The subjects' reaction times were increased both when the command stimulus was embedded in a distracting matrix ("noise"), and when an incompatible response was required. The effect of these two variables on reaction time was additive, indicating that each operates at a different "stage" of processing. There are good grounds for assuming that distracting characters affect the evaluation of the stimuli, while response compatibility affects the response selection and execution processes. It turned out that P300 latency was affected solely by the presence of the distracting characters. The need to perform an incompatible response, while increasing reaction time, had no effect on P300 latency. This pattern of results provides strong support for our interpretation of P300 latency.

The relation between reaction time and P300, when investigated, is quite complex. McCarthy, Kutas, and Donchin (1979; McCarthy & Donchin, 1979) were able to show in a similar experiment that when subjects err, the latency of P300 is increased by some 150 msec. The subjects' errors lead to the insertion of an additional processing stage whose nature at this time is not clear (see Rabbitt & Rodgers, 1977). We cannot tell, from the data on hand, if the subjects were aware that they erred and if the longer latency of P300 on error trials is related to the subject's consciousness that she or he has erred. It has, however, been the case that on all the error trials, the subjects responded faster than they did on other trials. It is as if on these trials, the final terminal product (the response) is emitted without the subject's full control. The subject is displaying a "response bias." Yet, the subjects read the names correctly even when they err. Whether the delay in P300 is induced by the conscious recognition or the conflict between the response emitted and the correct reading of the names is a matter for further research. This unsolved problem does illustrate, however, the specific questions that can be raised within the context of the psychophysiological study concerning the nature of conscious processing. This matter is discussed in Section V.

The importance of distinguishing between products and processes must also be recalled in attempts to interpret changes in the amplitude of the P300 component. Consider, for example, a subject who is confronted with a Bernoulli series of events and who is instructed to predict

which of two events will occur on that trial. Let us label the two events *A* and *B* and consider a subject who has just now predicted that a *B* will occur on the next trial. No doubt, the subject is aware of the prediction. One might even be tempted to consider the overt prediction an introspective report by the subject on the contents of consciousness. The subject, in this view, apparently believes that a *B* will, or at least is more likely to, occur on the next trial. It is easy to rephrase the statement and say that the subject "expects" the *B* to occur on the next trial. Let us assume that the event that actually occurred on that trial is an *A*. The subject has been proved wrong. The prediction was *not* confirmed. We might be tempted to say that the subject's expectancy was violated and to predict that such disconfirmations would elicit a larger P300 than confirmations of the subject's predictions. We have claimed above, citing much evidence, that P300 is large if the eliciting stimulus violates the subject's expectations. Sutton, Tueting, Hammer, and Hakerem (1978) investigated the relationship between the degree to which stimuli confirm or disconfirm subjects' predictions and the amplitude of the related P300. The results they obtained were somewhat equivocal. In general, the relationship between "confirmation" or "disconfirmation" and the amplitude of the P300 has proved inconsistent. In a recent study by Chesney and Donchin (1979), no difference could be observed between the P300 elicited by confirming and by disconfirming stimuli. Even so, when the trials were sorted by the sequence of preceding stimuli, large variations in the amplitude of P300 were observed. That is to say, the pattern of results that has led Donchin and his colleagues to assert that the amplitude of P300 is proportional to the degree to which a stimulus violates the subject's expectancies was again observed in these data. Yet the subjects' expectations, as reflected by the subjects' predictions, failed to affect P300.

This finding can, of course, be interpreted as indicating that the generality of the assertion concerning the relationship between expectancy and P300 is limited. It is also possible to assert that these data suggest that the subject's predictions are *not* reflections of his or her expectations. Even though the subject is "predicting," the predictions cannot be taken, under the instructions given to the subject, as a necessarily veridical introspective report of the subject's beliefs concerning future events. The subject's explicit predictions may be determined by a host of factors, only a subset of which is the subjective probability assigned to the occurrence of an *A* or a *B* on the next trial. The overt predictions are generated in an interaction between the subjective probability assigned to the events and such factors as heuristics (Tversky & Kahneman, 1974), motivation, attention to the experiment, and the utility of risk taking (Cohen, 1972). The amplitude of P300 thus reflects

only one of the many processes that determine the prediction. Therefore, P300 amplitude need not stand in a direct relation to the subject's predictions. These predictions may or may not be veridical reports about the subject's consciousness. Detailed analyses of the relationship between the amplitude of P300 and the subject's prediction conducted by Chesney and Donchin (1979) suggest that the subject's perception of the probability of events is, in fact, reflected by the amplitude of P300 and that any relationship between the amplitude of P300 and the overt predictions is fortuitous.

What does such a pattern of results imply for the analysis of consciousness and for our interpretation of electrophysiological data? First, of course, it underlines the futility of simpleminded attempts to relate the behavioral terminal points, the "products," to electrophysiological data. It is more profitable to consider the vast complexity of human information-processing and the detailed nature of the component processes that lead to various behavioral outcomes. Electrophysiology can be useful in supporting a detailed componential analysis of human information-processing because it provides data about some of the component processes whose existence and behavior are opaque to the traditional technologies. But electrophysiology will be of service only if it is not forced to bear unsuitable explanatory burdens. We do not wish to imply that it will never be of use to try to relate aspects of consciousness to the patterns of electrophysiological data. We agree with Posner's assertion (1978) that it is in the province of psychology to try to ascertain the attributes of those information-processing activities that become conscious, and to find how unconscious activities affect the conscious. It is within this context that careful analyses of the component processes based, where possible, on the analysis of ERP data become crucial.

As a final example of the manner in which ERP data patterns are used to address specific issues relating to the degree with which awareness affects information processing, consider the results reported by Johnson (1979). Johnson presented subjects with a Bernoulli series whose parameter, the probability of event A , was varied every 40–80 trials. A series began with $P(A) = .33$ and $P(B) = .67$. After a randomly selected number of trials, no less than 40 and no more than 80, $P(A)$ was set equal to $.67$, and $P(B)$ was set equal to $.33$. This state of affairs continued for another 40–80 trials, and again the probabilities were reversed. In the first experimental condition, the subject was not informed that the probabilities were reversed. In fact, as far as the subject was concerned, he or she was presented with a long Bernoulli series where $P(A) = P(B) = .50$. The P300 elicited by both A and B were analyzed. At issue was the degree to which the "local" probability of events in the series would affect the P300 without the subject's aware-

ness of the probability reversals. Johnson found that even though the subjects were not aware of the changes in probability, the pattern of P300 amplitudes reflected the probability of the events within the short segments of the series. That is, the local computations of expectancy, if such are indeed reflected by P300, continued even though the subject was not aware that the basic probability parameters were changing.

One would conclude from this finding that the subject's awareness of the circumstances is not necessary for the information-processing activity reflected by the P300. This conclusion is reasonable, and true, as far as it goes. However, in a second experimental condition, results were obtained that also need to be considered. In that second condition, the subjects were told that the parameters of the Bernoulli series were reversed every so often. The subjects were instructed to detect the points at which the probabilities reversed. The fact that the subjects were now aware of the probability reversals did change the pattern of ERPs. These changes appeared, however, only in the segments of the series that began immediately after the probability parameter was changed, and they continued until the subject reported the detection. When the subject *became aware* of the reversals and *was trying* to detect them, the amplitude of P300 began to increase gradually from trial to trial. This increase was detectable some five trials before the subject reported the detection. The amplitude of P300 was largest just as the subject was about to report the detection. The amplitude returned to its expected value immediately after the detection. During the remaining trials, till the next transition point, the amplitude of P300 was determined by the local probability of the stimuli.

It appears, then, that the amplitude of P300 recorded during the transition phase does reflect the fact that the subject is aware of the changes. The interpretation of these data was discussed by Johnson (1979). The details are not germane to the present discussion. What is germane is that *while the pattern of ERP data is variable, the specific behavioral outcomes remain similar*. The differences in the ERP data can be explained by considering the detailed structure of the information-processing activities that underlie the contents of the limited-capacity system that is consciousness. The work reviewed in the previous two sections suffered because it attempted to ignore this important distinction between overt performance—the *final product* of information processing—and the rich content of the human mind.

V. THE ERPs AND CONSCIOUSNESS

As noted in the introduction, we assume that a conscious experience indicated by an introspective report implies activity in a neuronal pop-

ulation. This population is, of course, unspecified. There is, at present no information about which brain events constitute conscious experience. The studies we reviewed did not succeed in locating, or in otherwise identifying, these processes. The evidence, however, is strong that the endogenous components of the ERP are manifestations of brain processes that are involved in what are clearly "cognitive" activities. There is, of course, no necessary relationship between cognition and consciousness. Yet, information processing does affect consciousness at least in the sense that these cognitive processes play a significant role in determining the contents of consciousness or in modifying states of consciousness. Furthermore, brain processes that manifest themselves in introspective reports (i.e., are conscious in our terms) probably influence information processing by determining which information will be processed or by assigning relative weights to particular aspects or channels of information. Consequently, even though it is not known which brain events constitute consciousness, it is possible to discuss tentatively the manner in which the processes manifested by certain ERP components may be related to consciousness. This analysis has at least two purposes. It may help in bracketing the conscious process. As more is learned about the origin and the functional significance of the ERP, we might be led to an examination of the conscious processes. But even if this remote goal is not achieved, the ERP components might be used to judge the degree to which consciousness has entered into specific behavioral acts. In this way, the ERP becomes a tool for assessing, rather than understanding, consciousness.

A consideration of the circumstances in which the P300 component is observed suggests that whenever P300 occurs, the subject is conscious of the task-relevant information carried by the eliciting stimulus. In this sense, P300 can be used to index the occurrence of conscious processing. Under certain circumstances, ongoing EEG activity can also be used as an index of conscious processes, and a comparison of the inferences that can be derived from the EEG and from ERP components is instructive. The EEG, of course, can be used to infer the general state of consciousness of the subject. (Is the subject awake or asleep?) In the awake subject, the EEG can serve to index the subject's state of arousal. If the subject is asleep, the EEG may index the existence of dreams, though this point is controversial. The EEG, however, provides no data about the content of consciousness. This, as we have shown above, is also true of the ERP. When the experimenter knows about, or has control over, environmental stimuli, both the EEG and the ERPs can be used to indicate that certain kinds of conscious processing have occurred. For example, if the occurrence of a stimulus has caused a change from alpha to beta frequencies in the EEG, it may be inferred that the subject was

conscious of the stimulus (Sokolov, 1969). If, however, the subject is already generating EEG in the beta range, the experimenter cannot decide to which of several stimuli in the environment the subject is attending. In fact, there is no way of determining whether the subject is consciously aware of *any* aspects of stimuli in the environment, since the subject could be immersed in a fantasy that is associated with an activated EEG. In this regard, the EEG is more limited than ERPs. By contrast, in a situation where there are several sources of stimulation (e.g., in the famous cocktail party that so many cognitive psychologists seem to have attended), it is possible to infer from ERPs to which source of stimulation the subject is paying attention, based on the proportion of the stimuli coming from a given source that is associated with P300.

Consider the following experiment by Ritter and Vaughan (1969). Tones were delivered once every 2 sec. On the average, 1 in 10 of the tones was slightly reduced in intensity. The subject's task was to detect the weaker tones (targets) and to signal to the experimenter whenever a target was noticed by pressing a button. (In the terminology of this chapter, this response represented a subjective report that a target had been detected.) As expected, the rare targets were associated with P300, whereas the frequent stimuli did not elicit P300. While it is clear that the subject must have consciously perceived the detected targets, the absence of P300 on presentation of the nontargets does not indicate that the subject was unaware of them. Thus, the presence or absence of P300 does not uniquely indicate whether the subject is aware of the stimuli. Rather, the elicitation of P300 by some stimuli in the series indicates that task-relevant information has been extracted from the series. These points may perhaps be best summarized by a consideration of the circumstance in the Ritter and Vaughan study that nondetected targets were *not* associated with P300. The latter, in other words, elicited only the obligatory components and thus were similar in waveshape to the ERPs elicited by the nontargets. The absence of P300 on presentation of the nondetected targets does not necessarily indicate that the subject did not hear them. What can be inferred is that the subject did not consciously perceive the *change* in intensity. Thus, presence of P300 indicates that the subject must have been conscious of the stimulus (in order to perceive the change and report it by the motor response), but the absence of P300 is uninformative, by itself, on this question.

Up to this point, the emphasis has been on ERP components that index the conscious awareness of task-relevant information (P300). However, whereas the ERP component can index brain events that affect the brain processes that constitute conscious experience, brain processes also can affect brain events, related to information processing, that do not constitute conscious experience. The "selective attention" effect, for

example, that was reported by Hillyard and his associates (Hillyard, Hink, Schwent, & Picton, 1973) could not occur unless the subject consciously understood the instructions given by the experimenter to count the targets in particular channels and also had a conscious intention of cooperating and performing the experimental requirements. The stimulus selection process indexed by the ERP, which presumably occurs outside awareness, can thus be modulated by brain processes associated with consciousness. A somewhat similar situation pertains to P300. As reported in Section IV, when a list of names, 80% male and 20% female, was presented, and subjects were asked to count the male names, P300 was larger in amplitude for the male names than for the female names (Kutas *et al.*, 1977). This result could occur only if the subjects consciously understood the categories involved and the meaning of the words presented (cf. presenting the names in an alphabet unfamiliar to the subject). In another study, the subjects were presented with 15 numbers in random fashion and were instructed to press a button whenever any of the numbers was repeated on two trials in a row (Friedman, Ritter, & Simson, 1978). All of the numbers were potential targets and occurred with equal probability, but the repeated numbers elicited larger P300s than the other numbers. The subjective expectation in these two experiments, therefore, was determined by the nature of the class of stimuli that the subjects were attempting to identify, and not by the probability of the specific stimuli. Thus, the subject's conscious understanding of the stimulus categories in both of these experiments established the nature of the subjective expectations; this understanding modified the brain activities that processed the task-relevant information in such a way as to produce the differential P300 results for the two classes of stimuli.

Another ERP component that appears to be related to consciousness is the contingent negative variation (CNV). As we noted in Section I, the CNV is a slow negative shift that occurs between two stimuli, for example, in warned reaction-time (RT) studies where there is a constant interval of 1 sec between a warning stimulus and a target stimulus. The CNV is an endogenous ERP because mere presentation of stimuli is not sufficient to elicit the CNV; the subject must be performing a task in which the stimuli play a role (Walter, Cooper, Aldridge, McCallum, & Winter, 1964). Thus, the appearance of the CNV indicates that the subjects have comprehended the task requirements and intend to cooperate in the performance of their task. Cooper, Pocock, McCallum, and Papakostopoulos (1978) have suggested that "subjective awareness might well be considered a key factor in experimental conditions in which the CNV is observed." In developing their theory, Cooper *et al.* reported that overlearning in a warned, simple RT task is associated

with diminution of the CNV, whereas RT performance in this task remains relatively constant. These data are interpreted by Cooper and colleagues in the following way. In the beginning of the experiment, the subjects must pay attention to the stimuli and their responses in order to learn and perform the task efficiently. As overlearning progresses, the subjects shift to an automatic mode of handling the task that occurs mainly or entirely outside awareness. An analogy outside the laboratory is the degree to which a novice must consciously pay attention to driving a car, compared with that paid by people after extensive experience in driving. In commenting on the Cooper *et al.* (1978) position, Naatanen (1978) suggested that the CNV appears to "mainly reflect conscious effort," which may overlap, and at times even interfere with, performance, depending on the circumstances (cf. paying too much attention to one's feet while dancing). The CNV, therefore, can be thought of as reflecting brain activity modulated by conscious involvement in certain experimental tasks.

In summary, whereas the current evidence indicates that ERPs do not reflect brain activity that constitutes consciousness, certain ERP components do appear to be related to such brain activity, either by affecting it, by being affected by it, or by indexing its occurrence in relation to task-relevant information. This is, of course, only a small contribution of ERPs to the development of a psychobiology of consciousness, but it is a beginning. For further discussion of the relationship between ERPs and consciousness, see Ritter (1978, 1979).

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