ELECTROPHYSIOLOGY
OF COGNITIVE PROCESSING

Steven A. Hillyard and Marta Kutas

Department of Neurosciences, University of California San Diego,
La Jolla, California 92093

CONTENTS

INTRODUCTION

The "information processing" approach to human perception and cognition
emerged during the 1950s as a revolutionary departure from previous con-
ceptual frameworks (Haber 1974). Over the past 25 years or so, it has
assumed considerable influence over the theories and research designs of
most cognitive psychologists. Within this same time frame, computerized
techniques have evolved for examining the processing of sensory informa-
tion in the human brain at a physiological level. Small, phasic brain poten-

33

tials elicited in conjunction with sensory, cognitive, and motor events can be easily detected by means of noninvasive electrical recordings from the scalp. These "event-related potentials" (ERPs) are the far-field reflections of patterned neural activities associated with informational transactions in the brain. Much of the current research on ERPs has been directed toward identifying specific components of brain wave activity that signify the operation of information processing "stages" such as encoding, selecting, memorizing, decision making, etc, using experimental designs borrowed from the domain of cognitive psychology. This convergence of paradigms and conceptual frameworks between psychological and physiological research into human information processing is the subject matter of the present review.

The scalp-recorded ERPs elicited by sensory signals (also known as evoked potentials) may be described in terms of a series of positive and negative peaks or components that occur at characteristic times. Some of the short-latency components represent activity in the peripheral sensory pathways such as the auditory brainstem relay nuclei (Waves I-VI in Figure 1). Most of the earlier ERP components (occurring before 80 msec) vary as a function of physical stimulus parameters and are relatively insensitive to changes in information processing demands; hence, they have been termed "exogenous" or "stimulus bound." In contrast, some of the longer latency components only appear in conjunction with specific perceptual or cognitive processes and are considered to be "endogenous." Two of the most widely studied endogenous components are the "Nd" wave, elicited by auditory signals that belong to an attended source or channel of input, and the P3 or P300 wave, which follows signals that occur unexpectedly and provide task-relevant information (Figure 1).[1]

A major goal of the emerging field of "cognitive psychophysiology" (Donchin 1982) is to identify particular ERP components as markers of specific aspects or stages of information processing. This can be accomplished through painstaking determinations of the ERP's responsiveness to different task demands and its relationships with behavioral measures of the process in question. Once validated in this way, ERP measures can clarify the timing, ordering, and interactions of the intermediate processes that are engaged in specific cognitive activities and lead to inferences about the mechanisms of parallel, serial, or hierarchical processing. Used as "converging operations" with behavioral measures, ERP data can also assist in the classification of perceptual, cognitive, and linguistic processes. While

---

[1]Two different labeling systems for ERP components are in common use. The polarity of the component is designated by P or N, and this may be followed by a small number or letter (P3, Pa, etc) that specifies its ordinal position in some particular wave sequence, or by a larger number (P300, N156, etc) that refers to its mean latency of occurrence in milliseconds.

ONGOING EEG

AUDITORY EVENT-RELATED POTENTIAL
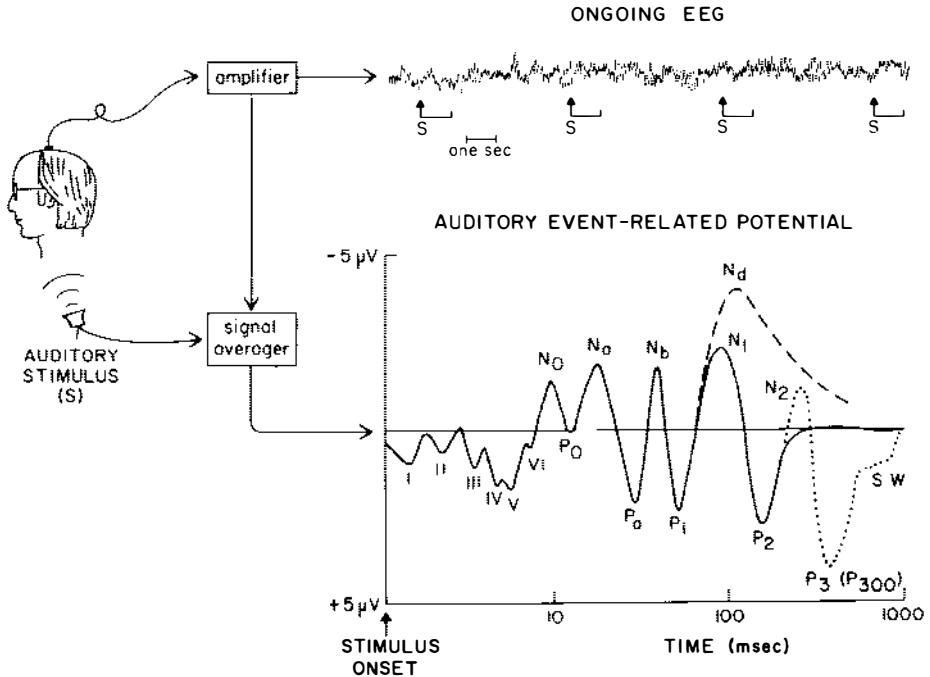
Figure 1   Idealized waveform of the computer-averaged auditory event-related potential (ERP) to a brief sound. The ERP is generally too small to be detected in the ongoing EEG (top) and requires computer averaging over many stimulus presentations to achieve adequate signal/noise ratios. The logarithmic time display allows visualization of the early brainstem responses (Waves I-VI), the midlatency components (No, Po, Na, Pa, Nb), the "vertex potential" waves (P1, N1, P2), and task-related endogenous components (Nd, N2, P300, and slow wave).

qualitative differences in ERP patterns imply the operation of distinctive processing modes, an equivalence of ERP waveforms across tasks provides converging evidence for postulating a common stage of processing. Ultimately, as the physiological generators of the endogenous ERPs are identified
localize the brain systems that participate in specific cognitive activities (Galambos & Hillyard 1981).

The relationship of endogenous ERPs to cognitive processing has been examined thoroughly in several recent symposia (Callaway et al 1978, Otto 1978, Desmedt 1979, Begleiter 1979, Lehmann & Callaway 1979, Kornhuber & Deecke 1980, Galambos & Hillyard 1981, Donchin 1982). The present review concentrates on developments in this field subsequent to the coverage by Beck (1975) and John & Schwartz (1978) in the *Annual Review of Psychology.*

SELECTIVE ATTENTION

Theories of attention have traditionally been divided on the question of whether stimulus selections occur at an "early" or "late" stage of processing, or at both. Early selection theories assumed a rapid rejection of irrelevant stimuli based on a cursory examination of their physical properties by means of a hypothetical "filter" or "stimulus set" process (e.g. Broadbent 1971). Late selection models, in contrast, proposed that stimuli are analyzed in considerable detail before any selections take place (e.g. Norman 1968). This classic controversy still simmers, and evidence for both types of mechanisms is abundant (e.g. Keele & Neill 1978, Bookbinder & Osman 1979). There is now a large body of ERP evidence bearing on this "level of selection" issue. As described below, it appears that information about different stimulus features becomes available to attentional mechanisms at different times, depending upon stimulus and the task requirements.

Subcortical Gating

One possible mechanism for early stimulus selection involves the suppression or gating of irrelevant inputs at the peripheral levels of the sensory pathways (Hernandez-Peon 1966). A related proposal has implicated the modulation of sensory transmission at specific thalamic relay nuclei under the control of frontal cortex and midbrain reticular formation (Skinner & Yingling 1977). A number of animal investigations have supported the idea that selective gating of inputs to the cortex can occur as a function of stimulus relevance (Gabriel et al 1975, Olesen et al 1975, Oatman & Anderson 1977).

Since the earliest components of the scalp-recorded ERPs represent evoked neural activity in specific subcortical pathways (auditory) or primary cortical receiving areas (somatosensory), the possibility of subcortical gating during attention can be readily investigated in man. The click-evoked brainstem potentials reportedly remain invariant in the face of attentional shifts (Picton & Hillyard 1974, Picton et al 1971, Woods & Hillyard 1978), suggesting that peripheral modulation either was not operative or was not detectable in the tasks used. The midlatency click-evoked components between 10 and 50 msec were similarly insensitive to various attentional manipulations. More recently, however, Lukas (1980, 1981) has reported that components I (auditory nerve) and V (midbrain) of the tone-evoked potential from the brainstem were increased in amplitude and/or reduced in latency when the tones were attended. The modulation of auditory nerve activity was attributed to inhibitory influences on the hair cell receptors via the olivo-cochlear pathway under the control of higher centers. These promising results need to be followed up to determine the range of conditions under which subcortical modulation of auditory input may occur (e.g.

whether it occurs more readily with tones than with clicks) and whether it reflects an effective stimulus selection mechanism.

The primary cortical components of the somatosensory ERP were studied in an elegant experiment by Desmedt & Robertson (1977), wherein subjects switched attention between sequences of shocks applied to fingers of the two hands. The primary components with latencies between 20 and 40 msec were not sensitive to shifts of attention between the hands. Velasco et al (1980) similarly found that early cortical and subcortical (N20-P30) components, the latter recorded through depth probes, did not vary among conditions of attention (responding to evoking shocks), distraction (ignoring shocks), or inattention (responding to shocks on the opposite side). On the other hand, Lavine et al (1980) reported that the somatosensory P30 component was augmented during attention to a sequence of shocks in comparison with a distraction condition (mental arithmetic). Since their P30 measure was made with reference to an extended baseline or to the N70 peak, however, it is not clear whether attention-related modulation occurred in the primary cortical components themselves. By and large, present evidence does not seem conclusive on whether or not subcortical gating plays a substantive role in human selective attention.

Early Auditory Selection

A reliable ERP index of early selective attention has been reported under conditions where auditory stimuli were delivered in random order at rapid rates over two or more sensory channels[2] (Hillyard et al 1973, 1978). Under these "high load" conditions, auditory stimuli belonging to the attended channel elicited a broad negative ERP which began as early as 60–80 msec and increased the measured amplitude of the evoked N1 component. In most studies of this early ERP, attention was directed to one channel at a time by requiring subjects to detect "targets" that deviated slightly in some parameter (pitch, intensity, or duration etc) from the nontargets. The enhanced negativity was elicited by all stimuli, targets and nontargets alike, that shared the easily discriminable "channel cues" with the attended tones (Hink et al 1978c, Okita 1981, Donald & Little 1981). By presenting attended and unattended stimuli in random order and alternating attention between channels, this experimental design controlled for nonselective influences on the ERP due to global arousal or alertness factors (Naatanen 1975, Hillyard & Picton 1979).

Initially, this early attention effect was viewed as an augmentation of the evoked N1 wave to attended-channel stimuli (Hillyard et al 1973), but recent studies have made it clear that the negativity can extend well beyond

[2]The term "channel" is used here to designate the sensory cue characteristics that distinguish attended from unattended stimuli (e.g. ear of entry or tone frequency).

the normal time course of the N1 and is primarily endogenous in nature (Naatanen & Michie 1979, Okita 1979, Hansen & Hillyard 1980). This attention-related component, termed "processing negativity" by Naatanen and associates, can be readily visualized and quantified as the negative "difference wave" (Nd) between the ERP to stimuli in an attended channel minus the ERP to the same stimuli when they are not attended (that is, when another channel is attended, see Figure 2). The Nd has been resolved into two distinct phases; the second lasts up to several hundred milliseconds and is more frontally distributed than the first (Hansen & Hillyard 1980).

Because of its short latency of onset, the Nd effect was interpreted by Hillyard et al (1973) as a sign of an early mode of stimulus selection akin to the "stimulus set" or "filter" of Broadbent (1971) or the "input selection" of Treisman (1969). Naatanen (1982) has suggested that "a selective facilitation state in the sensory system" may provide the mechanism for stimulus
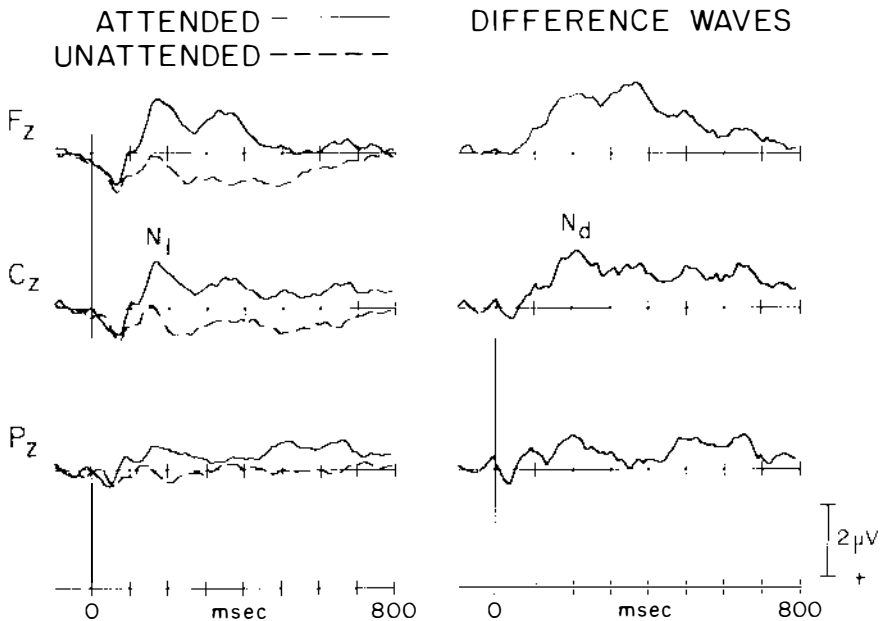
Figure 2 ERPs associated with selective attention to one of two channels of tones, in this case distinguished by frequency cues alone (300 Hz vs 700 Hz). High and low frequency tones were presented in random order at a rapid rate (about 3 per second). Subjects attended to one channel at a time, attempting to detect targets of longer duration therein. Attended-channel tones elicited a broad negative ERP, seen most clearly in the attended minus unattended difference waves (right). ERPs recorded from frontal (Fz), central (Cz), and parietal (Pz) scalp areas were averaged over several hundred stimulus presentations using a computer routine that extracts overlapping time epochs for stimulus presented at short intervals (Hansen & Hillyard 1982).

set. It is important to note in this connection that the *psychological* concept of a stimulus set or filter need not operate by means of a *physiological* gating or filtering mechanism (that is, by a simple modulation of exogenous activity) (Hillyard 1981a). Rather, a stimulus set implies that stimuli are selected rapidly and efficiently at an early stage of processing on the basis of some "distinct and conspicuous physical properties" (Keren 1976). This may be contrasted with a "response set" or "cognitive selection" whereby stimuli are distinguished by acquired categories of meaning, and hence must be analyzed more fully. Response set selections are associated with components later than the Nd, in many cases with the P300 component (Hillyard et al 1978).

Recent evidence has been generally supportive of the hypothesis that Nd is a neural sign of an early, stimulus set selection. This attention effect can be produced when channels are distinguished by a variety of physical cues (frequency, location, or intensity), and its latency of onset increases when the discrimination of the channel-cue is made more difficult (Hansen & Hillyard 1980). Okita (1979) has demonstrated nicely that the Nd effect appears when subjects attend to a moving channel of tones that shifts continuously in frequency and spatial location. Since a delayed Nd also can develop when the channels to be attended differ along more complex acoustic dimensions (e.g. the syllables "ba" vs "pa"), it appears that the speed of interchannel discrimination may be the limiting factor in allowing this attention effect to occur (Dickstein et al 1981).

If the Nd component reflects stimulus set selection, it follows that stimuli belonging to the rejected channel (and eliciting less early negativity) should not be processed to the same extent as those belonging to the attended channel. The consistent finding that target stimuli within the attended channel elicit much larger P300 components than do targets in the unattended channel has been taken to support such a hierarchical processing contingency (Hillyard et al 1978); stimuli that are rejected by the stimulus set do not reach the higher levels of analysis reflected in the P300. This conclusion must be tempered, however, by our incomplete understanding of the P300 wave, which is generally elicited by task-relevant stimuli that occur unexpectedly and require a motor response or cognitive decision. For instance, if the P300 is a sign of the "closure" of a decision process (Desmedt 1981) or a postdecisional updating of memory (Donchin et al 1978), then an absent P300 to targets in the unattended channel need not signify absence of perceptual processing of that channel.

Stronger evidence for an early perceptual selection has been obtained in a study where subjects listened selectively to one of four channels of tones, defined by two levels of frequency, each presented at two spatial locations (Hansen & Hillyard 1982). In some conditions, one of the two channel cues

was made more difficult to discriminate than the other by moving the two frequencies or two spatial locations closer together. The ERPs to the tones in the attended channel and in the other channel that shared its easily discriminable attribute both showed an early Nd effect (at about 70 msec) in relation to tones in the channels that lacked the proper level of this attribute. About 100 msec later the attended channel ERP diverged from the ERP to tones that differed only along the less discriminable attribute. This ERP pattern suggests a hierarchical selection mechanism whereby tones are first selected (or rejected) on the basis of their easily discriminable attributes and then examined for more subtle cue characteristics. Most importantly, tones that were rejected for lacking the easily discriminable cue showed no ERP evidence of further analysis of their less discriminable attributes. This was taken as evidence against a single stage, late selection model.

There is general agreement that the Nd is a neural sign of some aspect of stimulus processing that follows the stimulus set selection, rather than the selection process itself (Naatanen & Michie 1979, Hillyard 1981a). Several proposals have been advanced: (a) Nd reflects the further analysis of attended-channel stimuli for their task relevant properties; (b) Nd is elicited to the extent that a stimulus matches or fulfills the cue specifications of the attended channel; and (c) Nd is associated with the maintenance and rehearsal of the cue characteristics of attended events in a short-term memory store (Picton et al 1978, Naatanen 1982).

In support of the "further analysis" hypothesis, Okita (1981) found that placing a target-defining pitch shift at the end of tone bursts in a two-channel attention task resulted in a delay of the buildup of Nd in relation to when the target information was provided at the onset of the tone. Moreover, the early phase of the Nd to standard tones was augmented when targets were presented more frequently (Donald & Little 1981) or when the tones were made more difficult to discriminate from a background noise (Schwent et al 1976). These results are difficult to account for under the "cue match" hypothesis. However, contrary to the predictions of the "further analysis" hypothesis, Parasuraman (1980) found that a moderate increase in the difficulty of the standard-target discrimination did not alter the Nd amplitude substantially in a two-channel selective attention task. Clearly, further work is needed to determine the precise role played by the Nd in selective auditory processing.

Early Somatosensory Selection

Desmedt & Robertson (1977) found that paying attention to shocks applied to one hand resulted in an early negative ERP to those stimuli, beginning at around 75 msec. This attention-related negativity augmented the ampli-

tude of the N140 component and in some cases appeared to have an extended duration similar to the auditory Nd wave. The Nd to somatosensory stimuli was distinctive, however, in having an asymmetrical scalp distribution; it was larger over the sensory-motor cortex contralateral to the stimulated limb. At present it is not clear whether this negativity is entirely endogenous or includes some modulation of exogenous components.

Early Visual Selection

The relationship of visual ERPs to selective attention seems to be more complex than that in other modalities, with a variety of different components showing attention effects. The earliest visual changes identified so far occur during selective attention to spatial location, with subjects attending to flashing lights in one visual field while ignoring a concurrent sequence in the opposite field (Eason & Ritchie 1976, Van Voorhis & Hillyard 1977, Harter et al 1982). Attended-field flashes elicit ERPs with enlarged parieto-occipital components, including P1 (80–110 msec), N1 (160–180 msec), and P2 (200–250 msec) waves, together with a frontal-central N1 wave (150–170 msec) that lacks the prolonged duration of the auditory Nd component. Based on the polyphasic nature of the attention effect and its early onset, Eason & Richie suggested that it may arise from a gating of visual input at subcortical levels. The parieto-occipital components were largest over the hemisphere contralateral to the attended flashes. Hillyard (1981b) noted certain functional similarities between these ERPs in man and attention-related modulations of single unit discharge in the parietal lobe of trained monkeys.

Selective attention to other types of visual cues is manifested in specific configurations of ERP components. The cues (and the associated ERPs) that have been studied include the following: brightness (P200, Wastell & Kleinman 1980), color (N235, Harter et al 1982), spatial frequency (N160-350, Harter & Previc 1978), spatial orientation (N125, Harter et al 1979), contour (N150-235, Harter & Guido 1980), and alphanumeric characters (P250 and P450, Wastell & Kleinman 1980, Hillyard et al 1982). Since these attention-sensitive components differ in scalp distribution as well as in polarity and latency, they can be exploited to analyze the time course of the extraction of specific cue information from complex visual stimuli.

Multidimensional Stimulus Selection

There is current theoretical interest in the processing mechanisms that allow the separate attributes or dimensions of a compound stimulus to be integrated into a unified perceptual event (Miller 1978, Treisman & Gelade 1980). Do our attention mechanisms select the individual stimulus attributes of a multidimensional stimulus independently of one another or do

we attend to the configuration of attributes (i.e. to the "object" itself)? It is possible to approach this question by recording ERPs to dual-attribute stimuli in a task where the attended events are defined as a conjunction of the attributes. The general design calls for presentation of randomized sequences of four stimuli, each having one of two levels of two attributes "A" and "B" (A1B1, A2B1, A1B2, and A2B2). When attention is directed toward each of these compound stimuli in turn, independent selection of the two attributes would be implied if the following relationship held among their ERPs:[3]

$$ERP (A*B*) - ERP (AB*) = ERP (A*B) - ERP (AB)$$

In other words, the ERP difference associated with selection of attribute A should not differ as a function of the level of attribute B. This type of equation has considerable generality for testing the independence of two processes using ERPs (Kutas & Hillyard 1980a).

This type of design was employed nicely by Harter and colleagues (1979). Subjects attended to one of four line gratings that were oriented either horizontally or vertically and had line widths of either 9 or 36 min. An early negative phase of the ERP obeyed the above equation, suggesting that selective attention resulted in independent analyses of the size and orientation features. Later components (beyond 250 msec), on the other hand, were specific to the attended conjunction (Harter 1982). It was concluded that selection takes place in two overlapping stages ("feature specific" and "conjunction specific"), and that the early selection may reflect modulation of activity in orientation-specific cortical channels.

A similarly structured experiment in the auditory modality revealed a different pattern of processing interactions. Hansen & Hillyard (1982) presented subjects with four channels of tone pips (high or low in frequency, at right and left locations), under instructions to detect occasional, longer duration tones in one channel at a time. When the two cues were highly discriminable, a large Nd was elicited only by tones in the attended channel (having the attended conjunction of frequency-location attributes). This ERP pattern argues against an independent feature selection mechanism for auditory frequency and localization. It was also found that delays in the onset latency of Nd brought about by reducing the discriminability of the channel-defining attributes were not paralleled by increases in either RT or

[3]A star beside a letter signifies that the ERP is recorded under a condition where that attribute is relevant. For example, A*B* refers to the attended stimulus compound, while A*B designates the ERP to the stimulus that shares attribute A but not B with the attended compound.

P300 latency to the longer duration targets. This was taken as supporting a "parallel contingent" model of cue selection (e.g. Hawkins 1969) wherein the duration attribute is processed in parallel with the channel attributes. A stimulus is rejected as soon as evidence accrues that any one of the attributes fails to match the target specifications.

ERP evidence has been used to reveal the ordering of cue selections to other types of stimuli as well. Harter & Guido (1980) found that the selection of linear grating patterns from diffuse flashes occurred in two distinct stages; an early ERP negativity (starting at 150 msec) registered the presence or absence of contour in the stimulus, while a later negativity (after 200 msec) was specific

Harter et al (1982) have found that selection for location is manifest in the ERP prior to the selection for stimulus type (color and shape). They concluded that selection of relevant information is mediated by a hierarchical progression of temporally overlapping processes, with more complex stimulus features extracted at longer latencies.

Properties of Attentional Channels

The notion of a "channel" in sensory processing has been applied rather loosely to specific sources of stimuli in the environment, to circumscribed zones of receptor surface, or to sets of neurons that are selectively tuned to particular stimulus features. The concept of an "attentional channel," on the other hand, may be defined in terms of the set of stimuli that is processed more effectively when attention is directed toward a member of that set (Shiffrin et al 1976). Defining

attention" is not circular, but rather describes how narrowly stimulus selection is focused along a particular dimension.

The "bandwidth" of an attentional channel may be investigated with ERP techniques by measuring the progressive decline in amplitude of an attention-sensitive component as a function of distance from the attended locus. Harter & Previc (1978) have examined the properties of spatial frequency channels in the visual system. Subjects attended to a checkerboard having squares of a particular size (spatial frequency) presented among others of different sizes. A broad negative ERP (latency 150–300 msec) was elicited over the occipital scalp by the attended stimulus; its amplitude was reduced for spatial frequences that were increasingly disparate in size from the attended value. This attentional "tuning curve" became more sharply focused upon the attended locus at longer latencies. The authors suggested that selective attention modulated activity in spatial frequency-specific

similar to the attentional channels (about one octave).

The properties of attentional channels in other modalities have not been

studied so systematically. In a study where tones were presented at five spatial locations with 45° separations between them, an Nd was elicited by the attended tones and by those at adjacent locations (Hink et al 1978a). While this suggests that the adjacent locations were included in the same attentional channel as the attended locus, the channel bandwidth for auditory spatial attention may well depend upon additional factors such as interstimulus interval (ISI), pitch cues, and task structure (cf Schwent & Hillyard 1975). For somatosensory attention, Desmedt & Robertson's (1977) data indicate that the attentional channel was broad enough to include at least two adjacent fingers, since shocks to either finger elicited equivalently enlarged N140 components when one was attended.

A central issue in the debate between early and late models of selective attention concerns the extent to which stimuli belonging to a presumably irrelevant or rejected channel are processed. While these early negative ERPs give some information on the breadth of an attentional channel, the P300 wave seems to be a particularly sensitive index of the degree of attention received by deviant stimuli in and out of the designated focus of attention. The P300 is generally largest for task-relevant stimuli, but deviant events within an attended sequence may elicit P300 waves even though they are not designated as task-relevant (Courchesne et al 1978, Roth et al 1978a). There is also evidence that deviant stimuli occurring on an irrelevant channel can elicit P300 waves if they are highly intrusive (e.g. N. K. Squires et al 1977), or if relevant and irrelevant channels are made less discriminable (Hansen & Hillyard 1982). Since the P300 waves to irrelevant stimuli habituate rapidly (Courchesne et al 1978) and correlate with behavioral measures of interference from the irrelevant events (N. K. Squires et al 1977), this ERP seems to index the extent to which attention is actively drawn to events outside the attended channel.

Infrequent stimuli that deviate from a repetitive auditory sequence elicit an earlier ERP complex that includes a negativity at about 200 msec (the N2, N200, or mismatch negativity) and a less consistent positivity at around 250 msec (the P3a) (N. K. Squires et al 1975, Snyder & Hillyard 1976, Ford et al 1976a,b, K. C. Squires 1977). Mismatch negativity is elicited by deviations in the pitch or intensity of tones in both attended and unattended channels (Naatanen et al 1980), and its amplitude appears to be determined primarily by the degree of deviation and stimulus probability. A somewhat earlier ERP (N140) is elicited by variations in the timing of repetitive sounds (Ford & Hillyard 1981). These mismatch negativities seem to reflect an automatic or preattentive registration of stimulus deviance from a steady-state background. This component may be a sign of the sensory template mismatch that has been postulated as a precursor to the orienting response (N. K. Squires et al 1975). If a deviant stimulus is processed

further, either because it belongs to an attended channel or is salient enough to cause a redirection of attention, a P300 wave generally appears.

Temporal Dynamics of Attention

The speed with which attentional sets can be developed and switched has recently been evaluated using ERP measures. In a selective listening task, Donald & Young (1980) found that the Nd associated with selecting between tones in the two ears emerged almost immediately over the first few stimuli of each block. This contrasts with the slower buildup of attentional selectivity reported with dichotic verbal stimuli (Treisman et al 1974). A long-term habituation of the Nd, suggestive of a loss of interchannel selectivity with time on task, was also reported, but its generality is questionable (Hink et al 1978b).

The time course of the Nd may also reflect changes in selectivity as a function of ISI. At shorter ISIs, various measures of the Nd have been reported to increase in amplitude and decrease in latency (Parasuraman 1978, 1980, Naatanen et al 1982a). These effects may reflect an intensified selective set and/or a more rapid selection process invoked to deal with the increased information load. This improvement in ERP selectivity may result from the more frequent reinforcement of the memory representation of the attended cues at shorter ISIs (Hillyard 1981a, Naatanen 1982). These studies raise the possibility of using such ERP criteria to track attentional shifts on a moment to moment basis.

Resource Allocation

The selectivity of human information processing is often discussed in terms of the allocation of "attentional resources" to different tasks or classes of stimuli (Navon & Gopher 1979). Since these hypothetical resources are allocated from limited capacity "pools," improvement in performance of one task (benefits) may be associated with decrements in performance of other tasks (costs) that draw on the same resource pool. Allocations of attention among competing input channels are also reflected in ERP amplitudes. When subjects were required to detect targets in two channels simultaneously (divided attention), the amplitudes of the auditory Nd (or the visual N150) to each channel were intermediate between those elicited by the attended and rejected channels during focused attention (Hink et al 1977, Van Voorhis & Hillyard 1977, Parasuraman 1978, Okita 1979). Dividing attention also delayed the onset of Nd at high rates of stimulation (Parasuraman 1980). The total negativity elicited per unit time over both channels remained nearly constant, however, suggesting that these ERPs were indexing the allocation of processing resources from a limited pool.

Allocations of attention between two competing tasks have also been assessed through variations in the P300 elicited by task-related stimuli. Isreal et al (1980a, b) recorded the P300 in a "secondary" tone detection task performed concurrently with "primary" tasks such as tracking a visual target with a joystick or detecting shifts in target trajectories. P300 amplitudes were attenuated when the perceptual demands of the primary task were increased (e.g. more elements to be tracked), but not when the response demands became more severe (increases in tracking dimensionality or bandwidth). This result was consistent with a large body of evidence indicating that P300 indexes the processing resources involved with stimulus recognition and classification rather than response selection and execution (see below). Since reaction time (RT) data failed to differentiate increases in perceptual load from response load, the ERP measure was critical for the demonstration of multiple resources drawn from functionally distinct pools. Recent experiments along these lines have demonstrated a reciprocal relationship between the P300s elicited by primary and secondary task stimuli as the difficulty of one task was manipulated (Kramer et al 1981). The nature of these processing interactions, however, seems to depend on the subjects' level of practice and the specific tasks involved.

DETECTION AND RECOGNITION

Signal Detection Experiments

The ERP elicited by a threshold level acoustic signal provides a sensitive index of whether or not the sound was correctly detected. Early experiments showed that a large P300 component was elicited by correctly detected signals (Hits) but not by signals that were "missed." Moreover, the amplitude of P300 on Hits increased when the detections were made with greater accuracy or with a stricter decision criterion (Paul & Sutton 1972, K. C. Squires et al 1973). Mistaken reports of signal presence (False Alarms) on trials where no signal was present were also associated with a large P300 wave as long as the decision was made with a high degree of confidence and was time-locked to the averaging epoch (K. C. Squires et al 1975). Correct reports of signal absence (correct rejections) also elicited a P300 to the extent that decisions had a low probability of occurrence and adequate time-locking (see also Kerkhof 1978).

These experiments indicate that equivalent types of decisions are associated with equivalent endogenous ERPs, regardless of the actual physical stimulus. Whether the decision was based on signal presence or absence, P300 amplitudes were enlarged for more confident decisions and for less expected outcomes. Accordingly, Ruchkin & Sutton (1978) proposed that

P300 amplitude is related to the amount of prior uncertainty resolved by a stimulus; in communication theory terms, P300 is increased to the extent that the "equivocation" in the message is reduced.

The auditory N1 and the P300 components show parallel increases in amplitude and decreases in latency as a function of rated confidence of signal detections (K. C. Squires et al 1973, Parasuraman et al 1982). This suggests that the N1 component might be an index of the amount of signal information received by the detecting system (the "sensory magnitude" parameter of signal detection theory), while the P300 reflects some aspect of the decision process which utilizes that information. C. R. Chapman et al (1981) similarly found that variations in the somatosensory N1-P2 (N157-P237) components closely paralleled signal detection measures of pain discrimination. The authors suggested that this ERP also modeled the "sensory event" of detection theory and reflected the magnitude of the discharge of neural populations concerned with the perception of painful dental stimulation.

Parasuraman et al (1982) found a close correspondence between N1 and P300 amplitudes when subjects were required both to detect and identify tones of different frequencies. The N1 and P300 waves increased in amplitude with confidence of detection, but the P300 and a late slow wave were additionally sensitive to whether or not the signal was correctly identified. The authors concluded that stimulus detection and recognition were based on the same buildup of neural information, with detection beginning prior to recognition. However, the ERP and behavioral data suggested that detection and recognition could be dissociated and represented partially independent, overlapping processes in perception.

An interesting property of the threshold-detection P300 is its very short recovery or refractory period (Woods et al 1980). Unlike the long-latency exogenous components, the P300 showed little amplitude decrement in response to multiple signals presented at rates of two or three per second. This implies that the P300 reflects endogenous neural processes that are reactivated fully for each perceptual decision. The rapid recovery of the P300 closely parallels the speed with which sensory decisions can be executed (the psychological refractory period), indicating that P300 is generated by a neural system that shares the refractory properties of the decision process itself.

The P300 appears to represent a common, modality nonspecific process in these experiments, having a similar scalp distribution for detections of threshold level signals in auditory, visual, and somatic modalities (Snyder et al 1980); visual signals elicited the largest P300 amplitudes under conditions of modality uncertainty, perhaps reflecting an attentional bias toward vision. The detection of realistic visual targets (vehicles) in a simulated

natural terrain is associated with especially large P300s that are visible on single trials (Cooper et al 1977).

Using a principal components analysis, Ruchkin et al (1980) showed that the ERP to detected threshold level tones could be dissected into overlapping P300 and slow wave components, which are confounded in conventional peak amplitude measures. While the P300 increased monotonically as a function of signal detectability, the slow wave showed the inverse relationship, suggesting that the slow wave may depend upon the level of task demands. Wilkinson & Seales (1978) warned that the P300 to detected tones also may be confounded with the positive-going offset of a prior contingent negative variation (CNV) component; reductions in the anticipatory CNV over a longer session may account for apparent reductions in the P300 with time on task. This thorny problem of how to disentangle multiple overlapping components is of increasing concern to investigators who wish to associate individual ERP configurations with specific aspects of information processing (Tueting 1978, Picton & Stuss 1980).

Recognition and Memory Matching

In the "oddball" type of experiment where subjects discriminate an infrequent "target" from a series of similar stimuli (e.g. Kutas et al 1977, Courchesne et al 1978), the elicitation of P300 is obviously contingent upon the recognition of the target. The appearance of P300 (and associated waves) thus depends upon those perceptual and mnemonic processes that underly stimulus recognition and classification. While the P300 is generally increased by assigning a task that makes a given class of stimuli relevant, there is evidence that P300 waves may be elicited by pictures (persons, places, paintings, etc) recognized by subjects given no task instructions other than to watch the "slide show" (Neville et al 1982c). This type of P300 clearly depends upon the subject's long-term memory for these familiar pictures and not upon performance of an assigned task to make differential responses.

Late positive ERPs are also elicited in tasks where a test stimulus must be compared with the short-term memory trace of a preceding stimulus (Posner et al 1973, Thatcher 1977, Sanquist et al 1980). In a classic series of experiments, Chapman and associates presented subjects with a randomized sequence of two numbers and two letters, with either numbers or letters designated as relevant (R. M. Chapman 1973, R. M. Chapman et al 1979, 1981). The second member of the relevant pair, which had to be compared with the first, elicited the largest P300 component. This would be expected if the P300 was triggered upon the recognition of stimulus relevance. The first relevant stimulus of the pair elicited a P250 component that correlated with behavioral measures of recall and was interpreted as a sign of storage

in short-term memory. Friedman et al (1981) also found that the ERPs to numbers in a task that required the memory-matching of successive stimuli contained several late positive components, some of which were correlated with the requirement for short-term memory storage and others with target recognition. It is becoming clear that several late positive components are elicited in the 300–600 msec range during recognition and decision tasks (e.g. Friedman et al 1978), and that current concepts of the psychological correlates of "the P300" may have to be refined accordingly.

ERPs IN CHILDREN   Specific configurations of late ERPs are also associated with stimulus recognition and classification in children and infants. In 6- to 8-year-olds, the recognition of an assigned letter is followed by a series of late waves including Nc (400 msec), P3 (700 msec) and Pc (950 msec) components (Courchesne 1978). With maturation there is a progressive diminution of the Nc and Pc waves, leaving the P300 as the most prominent component in the adult ERP to infrequent target stimuli. Courchesne suggested that the Nc was associated with the perception of "attention getting" events. In a color discrimination task, a late positive component at about 400 msec was found to characterize the target ERP of 5- to 8-year-old children (Kurtzberg et al 1979); this wave showed changes in laterality which were ascribed to the maturation of parietal association areas involved in nonverbal processing.

The frontally distributed Nc component was also found to be a reliable measure of visual discrimination in 4- to 7-month-old infants (Courchesne et al 1981). When a random sequence of photographs of two faces was shown to alert infants, the less frequently presented face elicited a much larger Nc wave. In a similar design with 3-month-old infants, Hofmann et al (1981) found that the more infrequent of two striped patterns elicited a larger late positivity (300–600 msec) over the posterior scalp. This type of paradigm where differential ERPs are recorded to frequent/infrequent or familar/unfamiliar stimuli offers a powerful approach for analyzing perceptual and cognitive development in both normal and mentally deficient children.

ERPS AND MENTAL CHRONOMETRY

Belying its name, the P300 component associated with the detection of task-relevant stimuli has been found to vary in latency from less than 300 to nearly 1000 msec poststimulus; its latency is systematically lengthened as a function of increasing task difficulty or complexity of stimulus evaluation (Donchin et al 1978). While many of the same factors that influence behavioral measures of processing time also alter P300 latencies, these two

metrics are dissociable and often display noncommensurate changes (e.g. N. K. Squires et al 1977).

Kutas et al (1977) manipulated the RT-P300 latency relationship by requiring subjects to perform simple or complex semantic categorizations in order to detect target stimuli during different response regimes. They found that under instructions stressing "speeded" responses the P300 latency-RT correlation was relatively low, whereas under "accuracy" instructions it was significantly elevated. It was proposed that P300 latency and RT are indices of the timing of different aspects of processing: while RT encompasses all the processes leading to a cognitive decision and behavioral response, the P300 latency is a pure measure of the duration of stimulus evaluation processes (encoding, recognition, and classification), independent of response selection and execution.

A direct test of this hypothesis was carried out by McCarthy & Donchin (1981). Stimulus evaluation time was manipulated by embedding a target word either in a matrix of # signs or within a confusable background of letters, while response selection was manipulated by changing the compatibility between the target word ("right" or "left") and the responding hand. The results showed that both visual "noise" and stimulus-response incompatibility increased RT to the target words, but only the presence of the "noisy" stimulus background had a significant effect on P300 latency.

Several researchers have taken advantage of this established relationship between P300 latency and stimulus evaluation time to assess alternative theories of perceptual processing. Duncan-Johnson & Donchin (1980) investigated the well-known reduction in RT that is seen for more highly expected events. Based on their finding that P300 latency and RT covaried as a function of target probability, they concluded that stimulus expectancy in choice RT situations influences both stimulus evaluation and response mobilization times. A similar approach has been employed to pinpoint the locus of interference in the Stroop color word test (Warren & Marsh 1979, Duncan-Johnson & Kopell 1981). In a standard Stroop task, RTs showed the usual interference effect between hue and word meaning. While the latency of the P300 remained invariant. This suggested that the Stroop effect was mainly attributable to response incompatibility rather than perceptual interference.

ERP investigations using the Sternberg memory matching paradigm have also revealed nonequivalent changes in P300 latency and RT, this time as a function of memory set size (Marsh 1975, Gomer et al 1976, Adam & Collins 1978, Roth et al 1978b). Both P300 latency and RT increased linearly with greater short-term memory load, but the slope of the function was steeper for RT (about 40 msec per item) than for P300 latency (about 25 msec per item). Given the close correspondence between P300 latency

and stimulus evaluation time, there is every reason to believe that the P300 latency is a better measure of memory scanning than is RT (R. M. Chapman et al 1981).

Ford and colleagues (1979) used the pattern of P300 latency-RT covariation in a Sternberg-type task to compare the speed of short-term memory processes in young and elderly persons. They found that the elderly were much slower in responding to a probe stimulus in or out of the memorized set and displayed a steeper slope of increasing RT as a function of memory set size. However, their P300 latencies were only slightly longer than those of the younger subjects and showed identical slopes as a function of set size, indicating that both groups evaluated the probe against items in memory at the same rate. Accordingly, the longer response times of elderly subjects were almost entirely attributable to delays in response mobilization rather than to slower speeds of short-term memory processes.

The P300 generally occurs as part of an endogenous complex of components in which it is preceded by a negative peak (the N2 or N200) and followed by a long-lasting slow wave. Unlike the P300, the N200 is modality specific, being largest over preoccipital areas for visual stimuli and over the vertex for auditory stimuli (Simson et al 1977). Its earlier onset and modality specificity have led to the suggestion that the N200 may well be even more closely coupled to stimulus evaluation processes than the P300. Ritter et al (1979) found that increasing the difficulty of target detections produced approximately equivalent increases in RT, P300 latency, and N200 latency, but the correlation between N200 latency and RT was greater than that between P300 and RT. Towey et al (1980) obtained similar delays in the N200 with increasing difficulty of an auditory intensity discrimination that required mental counting. The latencies of the N200 and P300 were also found to increase in close correspondence with one another when the relevant cue for decision was systematically delayed (Hammond et al 1979). These findings suggest that the discriminative processing indexed by N200 gives rise to the P300, which reflects the next phase of memory updating or decision closure.

Renault et al (1982) have distinguished two types of "N200" components in a visual RT task, one related to modality-specific processing (N220) and the other to an "orienting" response (N256). The interrelationships between ERP and RT measures were taken to be consistent with "parallel contingent" or "cascade" models of information processing. Naatanen et al (1982b) have similarly distinguished an early "mismatch negativity" (N2a), which registers modality-specific stimulus deviations, and a later N2b which occurs as part of the endogenous ERP complex (that includes the P300) associated with the shifting of attention toward a deviant stimulus.

LANGUAGE PROCESSING

Linguistic Categories

Several recent investigations have been aimed at identifying ERP signs of specific levels of language processing ranging from the phonetic to the semantic. Sometime ago, Wood and colleagues reported that the auditory ERP recorded from the left hemisphere differed as a function of whether the eliciting CV syllable had been analyzed for phonetic or acoustic (fundamental frequency) cues (see Wood 1975). Grabow et al (1980) failed to replicate these findings, although they did note that the ERPs to CV syllables were consistently smaller over the left than the right temporal recording sites. Molfese (1978, 1980) also recorded ERPs to CV syllables, vowels, and nonspeech sounds and reported that some of the systematic variability in the ERPs reflected the presence or absence of formant transitions while a different component varied with formant bandwidth.

The search for ERP manifestations of meaning has taken several distinctly different tacks. R. M. Chapman et al (1980) have studied the ERPs associated with Osgood's orthogonal dimensions of connotative meaning—evaluative, potency, and activity. From their analysis, Chapman et al concluded that ERPs contain information about connotative meanings that is independent of any particular word. Semantic content was evident in a combination of ERP components, with the evaluative dimension showing the strongest correlations.

Brown and associates (1976, 1980) have also compared the ERPs to words with different meanings. Their approach, however, was to compare homophones invested with different meanings either by a sentence context or by instructions that predisposed a particular interpretation. Consistent ERP differences were found between the noun and verb forms of homophones, with the largest waveform differences localized to the left anterior scalp regions. A detailed examination of the topography of the scalp field potentials revealed that the noun forms of the homophones elicited greater positivity anteriorly and greater negativity posteriorly than did the verb forms. This ERP effect was fairly consistent across languages, modalities, and individuals. At present it is not known whether these ERP differences are specific to the semantic or syntactic aspects of the homophones.

There are indications that ERPs reflect the division of the lexicon into "open class" or content words, such as nouns, verbs, and adjectives, and "closed class" or function words that include members of the minor lexical categories (prepositions, conjunctions, auxiliaries, articles, etc). Kutas & Hillyard (1982a) reported differences in scalp distribution between the ERPs elicited by words belonging to these two vocabulary classes in two different experiments. The ERPs associated with open class words were

characterized by a larger sustained positivity between 200–700 msec post-stimulus and by a greater left-right asymmetry in the 400 to 700 msec region than were the ERPs associated with the closed class words.

Effects of Context and Expectancy

Specific ERP components have been associated with the development and violation of semantic expectancies during reading. Kutas & Hillyard (1980a,b) reported that the ERPs to semantically anomalous words in otherwise meaningful sentences were marked by an enhanced centro-parietal negativity between 300 and 600 msec poststimulus (N400). The authors proposed that this N400 may be an electrophysiological sign of the interruption of sentence processing by a semantically inappropriate word and the attempt to reinterpret that information. Control experiments showed that nonlinguistic deviations in visually presented sentences did not elicit N400 components; for example, semantically appropriate words unpredictably presented in oversize boldface print were associated with ERPs characterized by a triphasic, late positivity.

Violations of grammatical structure that did not involve semantic incongruity were not associated with N400 waves (Kutas & Hillyard 1982a). Unpredictable grammatical errors such as incorrect noun-verb number correspondence or incorrect verb tense occurring in prose passages did not elicit clear N400 waves like those that followed semantic anomalies. These results indicate that the N400 component is not a general response to aberrant words in a sentence or prose passage but appears to be contingent on some aspect of semantic analysis. Unlike the P300 response to other surprising classes of stimuli, the N400 is relatively insensitive to manipulations of probability of occurrence of semantic anomalies and shows a slight but consistent right hemispheric predominance in amplitude and duration (Kutas & Hillyard 1982b).

We have recently undertaken a parametric evaluation of the relation between the N400 and word expectancy for terminal words in a group of sentences of which none were semantically anomalous. We borrowed 320 sentences for which Bloom & Fischler (1980) had established the degree of expectancy (Cloze probability) for alternative terminal words. The amplitude of the ERP in the 300 to 600 msec region to final words was highly correlated with the Cloze probability of those words, particularly for recordings taken over the posterior right hemisphere (r above 0.90 over 14 subjects). This suggests that the N400 effect is not contingent upon semantic incongruity but is instead a more general phenomenon that provides a graded measure of semantic expectancy in sentence contexts. These results link the N400 measure with a number of verbal processing phenomena that

depend upon expectancy (semantic priming, lexical decision making, word recognition, etc).

The enhancement of a negative component at around 400 msec has been observed in a number of other experiments where subjects were required to read, name, or make a decision about a word based on its semantic attributes. In a study where subjects judged pairs of words to be the same or different by a semantic criterion (Sanquist et al 1980), the ERPs to the semantic mismatches displayed an increased negativity at around 400 msec. Boddy & Weinberg (1981) also showed ERP waveforms having larger N400 components to words that did not belong to a previously named category. Similar results were obtained by Polich et al (1981) in experiments involving semantic category judgments; they concluded that a late negativity (300–500 msec) was elicited by stimuli that did not belong to the category expected by the subject.

Late negative ERPs in the 400 msec range have also been reported in response to single words that were read orally or pictures that were named out loud. Stuss et al (1982) found that both pictures and words elicited a double-peaked negativity that was similar in morphology to the N400 associated with "semantic incongruity," but it had a more frontal scalp distribution. In this experiment, the stimuli were not semantically anomalous but were unpredictable as to content. Thus, the associated late negativity might reflect some aspect of the semantic activations triggered by unexpected words and other meaningful stimuli.

Neville and colleagues (1982a) found a negative component peaking at 410 msec in response to visually presented words which subjects had to identify in writing. The N410 was largest over anterior temporal regions and differed markedly from the late negativities described above in its scalp asymmetry, being larger over the left than the right hemisphere. This asymmetry was largest for words in the right visual field, which also showed the largest behavioral asymmetry for recognition. This pattern of asymmetries was not evident in the ERPs recorded from congenitally deaf subjects under the same conditions, suggesting differences in hemispheric specialization for linguistic functions in persons with abnormal language experience (Neville et al 1982b).

The exact relationship of these late negativities to various aspects of semantic processing has yet to be established. Nonetheless, the sensitivity with which these ERPs reflect verbal contexts and expectancies suggests that they will prove useful for analyzing the mechanisms by which word meanings are accessed during reading. Converging studies of ERPs and eye fixation patterns during reading (Just & Carpenter 1980) should make it possible to measure the intake of semantic information on a word-by-word basis with minimal disruption of natural modes of language usage.

CONCLUSION

The recording of ERPs from the scalp makes it possible to study cognitive and linguistic processes with greater precision than can be achieved with behavioral techniques alone. By providing a "second window" into the information processing activities of the human brain, ERP data have proven helpful in teasing apart stimulus evaluation from response mobilization factors, in identifying hierarchical levels of stimulus selection, and in distinguishing serial from parallel stimulus analyses. In the area of linguistics, specific ERP configurations are associated with fundamental theoretical categories such as function/content words and semantic/syntactic levels of analysis. However, we should not be too surprised or disconcerted by occasional dissociations between observed ERP patterns and those expected on theoretical grounds. Indeed, it is unlikely that the physiological signs of information processing will always bear a one-to-one correspondence with the constructs inferred from behavioral data (Donchin 1979). Such dissociations should not be cause for despair, but rather serve as an impetus to formulate new hypotheses regarding the processing events in question.

As ERP components continue to be validated as markers of specific cognitive and linguistic processes, they will have increasing utility for evaluating clinical syndromes. Latency measurements of exogenous ERPs have already become standardized diagnostic tests for neurological diseases affecting the integrity of the sensory pathways (Starr 1978). On the other hand, some of the endogenous ERPs seem particularly well suited for evaluating syndromes that involve deficits of selective attention such as hyperactivity (Loiselle et al 1980) and schizophrenia (Hink & Hillyard 1978). Tests of memory function derived from P300 latency measures are being applied to conditions where deficiencies of recognition and storage have been implicated (e.g. Goodin et al 1978, Ford et al 1979). Severe forms of psychopathology such as autism are reportedly associated with unusual late ERP configurations (Novick et al 1980). The recent observations of ERPs specific to semantic processing open the way for electrophysiological assessment of reading disorders and other forms of language deficiency. Finally, there are indications that endogenous ERPs can assess the impact of altered early environments upon later cognitive and linguistic development (Neville et al 1982a,b).

The ERP methodology can also play a significant role in the search for neural substrates of cognition. The enormous gulf that separates the realm of cellular neurophysiology from the domain of behavior and cognition has made it exceedingly difficult to conceptualize the electrochemical bases of thought and action. Since ERPs reflect patterns of neuronal activity at the physiological level and are correlated with perceptual and cognitive acts at

the psychological level, they may provide a means for bridging this gap. A research strategy to this end would involve, first, identifying ERPs in animals that are homologous to those associated with known cognitive activities in man, and, second, characterizing their neuronal generators through invasive recording and lesioning techniques (Galambos & Hillyard 1981). This approach, supplemented by such evidence as is available from human patient ERP recordings and studies of localized cerebral metabolism (Lassen et al 1978), should yield new insights into the nature of the elusive connections between mind and body.

Literature Cited

Adam, N., Collins, G. I. 1978. Late components of the visual evoked potential to search in short-term memory. *Electroencephalogr. Clin. Neurophysiol.* 44: 147–56

Beck, E. C. 1975. Electrophysiology and behavior. *Ann. Rev. Psychol.* 26:233–62

Begleiter, H., ed. 1979. *Evoked Brain Potentials and Behavior.* New York: Plenum

Bloom, P. A., Fischler, I. 1980. Completion norms for 329 sentence contexts. *Mem. Cognit.* 8:631–42

Boddy, J., Weinberg, H. 1981. Brain potentials, perceptual mechanism and semantic categorization. *Biol. Psychol.* 12: 43–61

Bookbinder, J., Osman, E. 1979. Attentional strategies in dichotic listening. *Mem. Cognit.* 7:511–20

Broadbent, D. E. 1971. *Decision and Stress.* New York: Academic

Brown, W. S., Lehmann, D., Marsh, J. T. 1980. Linguistic meaning-related differences in evoked potential topography: English, Swiss-German, and imagined. *Brain Lang.* 11:340–53

Brown, W. S., Marsh, J. T., Smith, J. C. 1976. Evoked potential waveform differences produced by the perception of different meanings of an ambiguous phrase. *Electroencephalogr. Clin. Neurophysiol.* 41: 113–23

Callaway, E., Tueting, P., Koslow, S., eds. 1978. *Event-Related Brain Potentials in Man.* New York: Academic

Chapman, C. R., Chen, A. C. N., Colpitts, Y. M., Martin, R. W. 1981. Sensory decision theory describes evoked potentials in pain discrimination. *Psychophysiology* 18:114–20

Chapman, R. M. 1973. Evoked potentials of the brain related to thinking. In *The Psychophysiology of Thinking,* ed. F. J. McGuigan. New York: Academic

Chapman, R. M., McCrary, J. W., Bragdon, H. R., Chapman, J. A. 1979. Latent components of event-related potentials functionally related to information processing. See Desmedt 1979, pp. 80–105

Chapman, R. M., McCrary, J. W., Chapman, J. A. 1981. Memory processes and evoked potentials. *Can. J. Psychol.* 35:201–12

Chapman, R. M., McCrary, J. W., Chapman, J. A., Martin, J. K. 1980. Behavioral and neural analyses of connotative meaning: Word classes and rating scales. *Brain Lang.* 11:319–39

Cooper, R., McCallum, W. C., Newton, P., Papakostopoulos, D., Pocock, P. V., Warren, W. J. 1977. Cortical potentials associated with the detection of visual events. *Science* 196:74–77

Courchesne, E. 1978. Neurophysiological correlates of cognitive development: Changes in long-latency event-related potentials from childhood to adulthood. *Electroencephalogr. Clin. Neurophysiol.* 45:468–82

Courchesne, E., Courchesne, R. Y., Hillyard, S. A. 1978. The effect of stimulus devia-

tion on P3 waves to easily recognized stimuli. *Neuropsychologia* 16:189–99

Courchesne, E., Ganz, L., Norcia, A. M. 1981. Event-related brain potentials to human faces in infants. *Child Dev.* 52:804–11

Desmedt, J. E., ed. 1979. Cognitive components in cerebral event-related potentials and selective attention. In *Progress in Clinical Neurophysiology*, Vol. 6. Karger: Basel. 319 pp.

Desmedt, J. E. 1981. Scalp-recorded cerebral event-related potentials in man as point of entry into the analysis of cognitive processing. In *The Organization of the Cerebral Cortex*, ed. F. O. Schmitt, F. G. Worden, G. Adelman, S. D. Dennis, 19:441–73. Cambridge, Mass: MIT Press

Desmedt, J. E., Robertson, D. 1977. Differential enhancement of early and late components of the cerebral somatosensory evoked potentials during forced-paced cognitive tasks in man. *J. Physiol.* 271:761–82

Dickstein, P. W., Hansen, J. C., Berka, C., Hillyard, S. A. 1981. Electrophysiological correlates of selective attention to speech sounds. *Soc. Neurosci.* 7:452 (Abstr.)

Donald, M. W., Little, R. 1981. The analysis of stimulus probability inside and outside the focus of attention, as reflected by the auditory N1 and P3 components. *Can. J. Psychol.* 35:175–87

Donald, M. W., Young, M. 1980. Habituation and rate decrements in the auditory vertex potential during selective listening. See Kornhuber & Deecke 1980, pp. 331–66

Donchin, E. 1979. Event-related brain potentials: A tool in the study of human information processing. In *Evoked Brain Potentials and Behavior*, ed. H. Begleiter, pp. 13–88. New York: Plenum

Donchin, E., ed. 1982. *Cognitive Psychophysiology*. Hillsdale, NJ: Erlbaum

Donchin, E., Ritter, W., McCallum, W. C. 1978. Cognitive psychophysiology: The endogenous components of the ERP. See Callaway et al 1978, pp. 349–441

Duncan-Johnson, C. C., Donchin, E. 1980. The relation of P300 latency to reaction time as a function of expectancy. See Kornhuber & Deecke, pp. 717–22

Duncan-Johnson, C. C., Kopell, B. S. 1981. The Stroop effect: Brain potentials localize the source of interference. *Science* 214:938–40

Eason, R. G., Ritchie, G. 1976. *Effects of stimulus set on early and late compo-*

nents of visually evoked potentials. Presented at Psychon. Soc., St. Louis

Ford, J. M., Hillyard, S. A. 1981. ERPs to interruptions of a steady rhythm. *Psychophysiology* 18:322–30

Ford, J. M., Roth, W. T., Kopell, B. S. 1976a. Auditory evoked potentials to unpredictable shifts in pitch. *Psychophysiology* 13:32–39

Ford, J. M., Roth, W. T., Kopell, B. S. 1976b. Attention effects on auditory evoked potentials to infrequent events. *Biol. Psychol.* 7:65–77

Ford, J. M., Roth, W. T., Mohs, R. C., Hopkins, W. F., Kopell, B. S. 1979. Event-related potentials recorded from young and old adults during a memory retrieval task. *Electroencephalogr. Clin. Neurophysiol.* 47:450–59

Friedman, D., Vaughan, H. G. Jr., Erlenmeyer-Kimling, L. 1978. Stimulus and response related components of the late positive complex in visual discrimination tasks. *Electroencephalogr. Clin. Neurophysiol.* 45:319–30

Friedman, D., Vaughan, H. G. Jr., Erlenmeyer-Kimling, L. 1981. Multiple late positive potentials in two visual discrimination tasks. *Psychophysiology* 18:635–49

Gabriel, M., Saltwick, S. E., Miller, J. D. 1975. Conditioning and reversal of short-latency multiple-unit responses in the rabbit medial geniculate nucleus. *Science* 189:1108–9

Galambos, R., Hillyard, S. A. 1981. Electrophysiological approaches to human cognitive processing. *Neurosci. Res. Program Bull.* 20:141–265

Goodin, D. S., Squires, K. C., Starr, A. 1978. Long latency event-related components of the auditory evoked potentials in dementia. *Brain* 101:635–48

Gomer, F. E., Spicuzza, R. J., O'Donnell, R. D. 1976. Evoked potential correlates of visual item recognition during memory-scanning tasks. *Physiol. Psychol.* 4:61–65

Grabow, J. D., Aronson, A. E., Offord, K. P., Rose, D. E., Greene, K. L. 1980. Hemispheric potentials evoked by speech sounds during discrimination tasks. *Electroencephalogr. Clin. Neurophysiol.* 49:48–58

Haber, R. N. 1974. Information processing. In *Handbook of Perception*, ed. E. C. Carterette, M. P. Friedman, 1:313–34. New York: Academic

Hammond, E. J., Silva, D. A., Klein, A. J., Teas, D. C. 1979. A technique for separating endogenous from exogenous hu-

man cortical potentials. *Electroenceph-alogr. Clin. Neurophysiol.* 46:482–85

Hansen, J. C., Hillyard, S. A. 1980. Endogenous brain potentials associated with selective auditory attention. *Electroencephalogr. Clin. Neurophysiol.* 49:277–90

Hansen, J. C., Hillyard, S. A. 1982. Selective attention to multidimensional auditory stimuli in man. *J. Exp. Psychol: Hum. Percept. Perform.* In press

Harter, M. R. 1982. Discussion on selective attention. See Donchin 1982

Harter, M. R., Aine, C., Schroeder, C. 1982. Hemispheric differences in ERP measures of selective attention. See Stuss et al 1982

Harter, M. R., Guido, W. 1980. Attention to pattern orientation: Negative cortical potentials, reaction time, and the selection process. *Electroencephalogr. Clin. Neurophysiol.* 49:461–75

Harter, M. R., Previc, F. H. 1978. Size-specific information channels and selective attention: Visual evoked potential and behavioral measures. *Electroencephalogr. Clin. Neurophysiol.* 45:628–40

Harter, M. R., Previc, F. H., Towle, V. L. 1979. Evoked potential indicants of size- and orientation-specific information processing: Feature-specific sensory channels and attention. See Lehmann & Callaway 1979, pp. 169–84

Hawkins, H. L. 1969. Parallel processing in complex visual discrimination. *Percept. Psychophys.* 5:56–64

Hernandez-Peon, R. 1966. Physiological mechanisms in attention. In *Frontiers in Physiological Psychology*, ed. R. W. Russell. New York: Academic

Hillyard, S. A. 1981a. Selective auditory attention and early event-related potentials: A rejoinder. *Can. J. Psychol.* 35:159–74

Hillyard, S. A. 1981b. Visual selective attention. See Galambos & Hillyard 1981, pp. 240–42

Hillyard, S. A., Hink, R. F., Schwent, V. L., Picton, T. W. 1973. Electrical signs of selective attention in the human brain. *Science* 182:177–80

Hillyard, S. A., Picton, T. W. 1979. Event-related brain potentials and selective information processing in man. See Desmedt 1979, pp. 1–50

Hillyard, S. A., Picton, T. W., Regan, D. M. 1978. Sensation, perception and attention: Analysis using ERPs. See Callaway et al 1978, pp. 223–322

Hillyard, S. A., Squires, K. C., Squires, N. K. 1982. The psychophysiology of atten-

tion. In *Attention: Theory, Brain Function, and Clinical Applications*, ed. D. Sheer. Hillsdale, NJ: Erlbaum. In press

Hink, R. F., Fenton, W. H. Jr., Pfefferbaum, A., Tinklenberg, J. R., Kopell, B. S. 1978a. The distribution of attention across auditory input channels: An assessment using the human evoked potential. *Psychophysiology* 15:466–73

Hink, R. F., Fenton, W. H. Jr., Tinklenberg, J. R., Pfefferbaum, A., Kopell, B. S. 1978b. Vigilance and human attention under conditions of methylphenidate and secobarbital intoxication: An assessment using brain potentials. *Psychophysiology* 15:116–25

Hink, R. F., Hillyard, S. A., Benson, P. J. 1978c. Event-related brain potentials and selective attention to acoustic and phonetic cues. *Biol. Psychol.* 6:1–16

Hink, R. F., Hillyard, S. A. 1978. Electrophysiological measures of attentional processes in man as related to the study of schizophrenia. *J. Psychiatr. Res.* 14:155–65

Hink, R. F., Van Voorhis, S. T., Hillyard, S. A., Smith, T. S. 1977. The division of attention and the human auditory evoked potential. *Neuropsychologia* 15:597–605

Hofmann, M. J., Salapatek, P., Kuskowski, M. 1981. Evidence for visual memory in the averaged and single evoked potentials of human infants. *Infant Behav. Dev.* 4:401–21

Isreal, J. B., Chesney, G. L., Wickens, C. D., Donchin, E. 1980a. P300 and tracking difficulty: Evidence for multiple resources in dual-task performance. *Psychophysiology* 17:259–73

Isreal, J. B., Wickens, C. D., Chesney, G. L., Donchin, E. 1980b. The event-related brain potential as an index of display-monitoring workload. *Hum. Factors* 22:211–24

John, E. R., Schwartz, E. L. 1978. The neurophysiology of information processing and cognition. *Ann. Rev. Psychol.* 29:1-29

Just, M. A., Carpenter, P. A. 1980. A theory of reading: From eye fixations to comprehension. *Psychol. Rev.* 87:329–54

Keele, S. W., Neill, W. T. 1978. Mechanisms of attention. In *Handbook of Perception*, ed. E. C. Carterette, M. P. Friedman, 9:1–47. New York: Academic

Keren, G. 1976. Some considerations of two alleged kinds of selective attention. *J. Exp. Psychol: Gen.* 105:349–74

Kerkhof, G. A. 1978. Decision latency: The P3 component in auditory signal detection. *Neurosci. Lett.* 8:289–94

Kornhuber, H. H., Deecke, L., eds. 1980. *Motivation, Motor and Sensory Processes of the Brain: Electrical Potentials, Behavior and Clinical Use. Prog. Brain Res.*, Vol. 54. Amsterdam: Elsevier/-North Holland

Kramer, A., Wickens, C, Vanasse, L., Heffley, E., Donchin, E. 1981. Primary and secondary task analysis of step tracking: An event-related potentials approach. *Proc. Hum. Factors Soc., 25th Ann. Meet., Rochester, NY*

Kurtzberg, D., Vaughan, H. G. Jr., Kreuzer, J. 1979. Task-related cortical potentials in children. See Desmedt 1979, 6: 216–23

Kutas, M., Hillyard, S. A. 1980a. Event-related brain potentials to semantically inappropriate and surprisingly large words. *Biol. Psychol.* 11:99–116

Kutas, M., Hillyard, S. A. 1980b. Reading senseless sentences: Brain potentials reflect semantic incongruity. *Science* 207:203–5

Kutas, M., Hillyard, S. A. 1982a. Event-related brain potentials and cognitive science. In *Cognitive Neuroscience*, ed. M. Gazzaniga. New York: Plenum. In press

Kutas, M., Hillyard, S. A. 1982b. The lateral distribution of event-related potentials during sentence processing. *Neuropsychologia*. In press

Kutas, M., McCarthy, G., Donchin, E. 1977. Augmenting mental chronometry: The P300 as a measure of stimulus evaluation time. *Science* 197:792–95

Lassen, N. A., Ingvar, D. H., Skinhoj, E. 1978. Brain function and blood flow. *Sci. Am.* 239:62–71

Lavine, R. A., Buchsbaum, M. S., Schechter, G. 1980. Human somatosensory evoked responses: Effects of attention and distraction on early components. *Physiol. Psychol.* 8:405–8

Lehmann, D., Callaway, E., eds. 1979. *Human Evoked Potentials: Applications and Problems*. New York: Plenum

Loiselle, D. L., Stamm, J. A., Maitinsky, S., Whipple, S. C. 1980. Evoked potential and behavioral signs of attentive dysfunctions in hyperactive boys. *Psychophysiology* 17:193–201

Lukas, J. H. 1980. Human attention: The olivo-cochlear bundle may function as a peripheral filter. *Psychophysiology* 17: 444–52

Lukas, J. H. 1981. The role of efferent inhibition in human auditory attention: An examination of the auditory brainstem potentials. *Int. J. Neurosci.* 12:137–45

Marsh, G. R. 1975. Age differences in evoked potential correlates of a memory scanning process. *Exp. Aging Res.* 1:3–16

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

Miller, J. 1978. Multidimensional same-different judgements: Evidence against independent comparisons of dimensions. *J. Exp. Psychol: Hum. Percept. Perform.* 4:411–22

Molfese, D. L. 1978. Left and right hemisphere involvement in speech perception: Electrophysiological correlates. *Percept. Psychophys.* 23:237–43

Molfese, D. L. 1980. The phoneme and the engram: Electrophysiological evidence for the acoustic invariant in stop consonants. *Brain Lang.* 9:372–76

Naatanen, R. 1975. Selective attention and evoked potentials in humans—A critical review. *Biol. Psychol.* 2:237–307

Naatanen, R. 1982. Processing negativity-evoked potential reflection of selective attention. *Psychol. Bull.* In press

Naatanen, R., Gaillard, A. W. K., Mantysalo, S. 1980. Brain potentials correlates of voluntary and involuntary attention. See Kornhuber & Deecke 1980, pp. 343–48

Naatanen, R., Gaillard, A. W. K., Varey, C. A. 1982a. Attention effects on auditory EPs as a function of inter-stimulus interval. *Biol. Psychol.* 13:173–87

Naatanen, R., Michie, P. T. 1979. Early selective attention effects on the evoked potential. A critical review and reinterpretation. *Biol. Psychol.* 8:81–136

Naatanen, R., Simpson, M., Loveless N. E. 1982b. Stimulus deviance and event-related brain potentials. *Biol. Psychol.* In press

Navon, D., Gopher, D. 1979. On the economy of the human processing system. *Psychol. Rev.* 86:214–55

Neville, H. J., Kutas, M., Schmidt, A. 1982a. Event-related potential studies of cerebral specialization during reading. I. Studies of normal adults. *Brain Lang.* 16:300–15

Neville, H. J., Kutas, M., Schmidt, A. 1982b. Event-related potential studies of cerebral specialization during reading. II. Studies of congenitally deaf adults. *Brain Lang.* 16:316–37

Neville, H. J., Snyder, E., Woods, D. L., Galambos, R. 1982c. Recognition and surprise alter the human visual evoked response. *Proc. Natl. Acad. Sci. USA* 79:2121–23

Norman, D. A. 1968. Toward a theory of memory and attention. *Psychol. Rev.* 75:522–36

Novick, B., Vaughan, H. G. Jr., Kurtzberg, D., Simson, R. 1980. An electrophysiologic indication of auditory processing defects in autism. *Psychiatry Res.* 3: 107–14

Oatman, L. C., Anderson, B. W. 1977. Effects of visual attention on tone burst evoked auditory potentials. *Exp. Neurol.* 57:200–11

Okita, T. 1979. Event-related potentials and selective attention to auditory stimuli varying in pitch localization. *Biol. Psychol.* 9:271–84

Okita, T. 1981. Slow negative shifts of the human event-related potential associated with selective information processing. *Biol. Psychol.* 12:63–75

Olesen, T. D., Ashe, J. H., Weinberger, N. M. 1975. Modification of auditory and somatosensory system activity during pupillary conditioning in the paralyzed cat. *J. Neurophysiol.* 38:1114–39

Otto, D., ed. 1978. *Multidisciplinary Perspectives in Event-Related Brain Potential Research.* EPA 600/9–77–043. Washington DC: GPO

Parasuraman, R. 1978. Auditory evoked potentials and divided attention. *Psychophysiology* 15:460–65

Parasuraman, R. 1980. Effects of information processing demands on slow negative shift latencies and N100 amplitude in selective and divided attention. *Biol. Psychol.* 11:217–33

Parasuraman, R., Richer, F., Beatty, J. 1982. Detection and recognition: Concurrent processes in perception. *Percept. Psychophys.* 31:1–12

Paul, D. D., Sutton, S. 1972. Evoked potential correlates of response criterion in auditory signal detection. *Science* 177:362–64

Picton, T. W., Campbell, K. B., Baribeau-Braun, J., Proulx, G. B. 1978. The neurophysiology of human attention: A tutorial review. In *Attention and Performance*, ed. J. Requin, 6:429–67. Hillsdale, NJ: Erlbaum

Picton, T. W., Hillyard, S. A. 1974. Human auditory evoked potentials. II. Effects of attention. *Electroencephalogr. Clin. Neurophysiol.* 36:191–200

Picton, T. W., Hillyard, S. A., Galambos, R., Schiff, M. 1971. Human auditory attention: A central or peripheral process? *Science* 173:351–53

Picton, T. W., Stuss, D. T. 1980. The component structure of the human event-related potentials. See Kornhuber & Deecke 1980, pp. 17–49

Polich, J., Vanasse, L., Donchin, E. 1981. Category expectancy and the N200. *Psychophysiology* 18:142

Posner, M. I., Klein, R., Summers, J., Buggie, S. 1973. On the selection of signals. *Mem. Cognit.* 1:2–12

Renault, B., Ragot, R., Lesevre, N., Remond, A. 1982. Onset and offset of brain events as indices of mental chronometry. *Science* 215:1413–15

Ritter, W., Vaughan, H. G. Jr., Friedman, D. 1979. A brain event related to the making of a sensory discrimination. *Science* 203:1358–61

Roth, W. T., Ford, J. M., Kopell, B. S. 1978a. Long-latency evoked potentials and reaction time. *Psychophysiology* 15:17–23

Roth, W. T., Rothbart, R. M., Kopell, B. S. 1978b. The timing of CNV resolution in a memory retrieval task. *Biol. Psychol.* 6:39–49

Ruchkin, D. S., Sutton, S. 1978. Equivocation and P300 amplitude. See Otto 1978, pp. 175–77

Ruchkin, D. S., Sutton, S., Kietzman, M. L., Silver, K. 1980. Slow wave and P300 in signal detection. *Electroencephalogr. Clin. Neurophysiol.* 50:35–47

Sanquist, T. F., Rohrbaugh, J. W., Syndulko, K., Lindsley, D. B. 1980. Electrocortical signs of levels of processing: Perceptual analysis and recognition memory. *Psychophysiology* 17:568–76

Schwent, V. L., Hillyard, S. A. 1975. Auditory evoked potentials and multi-channel selective attention. *Electroencephalogr. Clin. Neurophysiol.* 38:131–38

Schwent, V. L., Hillyard, S. A., Galambos, R. 1976. Selective attention and the auditory vertex potential. II: Effects of signal intensity and masking noise. *Electroencephalogr. Clin. Neurophysiol.* 40: 615–22

Shiffrin, R. M., McKay, D. P., Shaffer, W. O. 1976. Attending to forty-nine spatial positions at once. *J. Exp. Psychol: Hum. Percept. Perform.* 2:14–22

Simson, R., Vaughan, H. G. Jr., Ritter, W. 1977. The scalp topography of potentials in auditory and visual discrimination tasks. *Electroencephalogr. Clin. Neurophysiol.* 42:528–35

Skinner, J. E., Yingling, C. D. 1977. Central gating mechanisms that regulate event-related potentials and behavior. In *Attention, Voluntary Contraction and Event-Related Cerebral Potentials. Prog. Clin. Neurophysiol.*, ed. J. E. Desmedt, 1:30–69

Snyder, E., Hillyard, S. A. 1976. Long-latency evoked potentials to irrelevant deviant stimuli. *Behav. Biol.* 16:319–31

Snyder, E., Hillyard, S. A., Galambos, R. 1980. Similarities and differences among the P3 waves to detected signals in three modalities. *Psychophysiology* 17:112–22

Squires, K. C., Donchin, E., Herning, R. I., McCarthy, G. 1977. On the influence of task relevance and stimulus probability on event-related potential components. *Electroencephalogr. Clin. Neurophysiol.* 42:1–14

Squires, K. C., Hillyard, S. A., Lindsay, P. L. 1973. Vertex potentials evoked during auditory signal detection: Relation to decision criteria. *Percept. Psychophys.* 14:265–72

Squires, K. C., Squires, N. K., Hillyard, S. A. 1975. Decision-related cortical potentials during an auditory signal detection task with cued observation intervals. *J. Exp. Psychol.: Hum. Percept. Perform.* 104:268–79

Squires, N. K., Donchin, E., Squires, K. C., Grossberg, S. 1977. Bisensory stimulation: Inferring decision-related processes from the P300 component. *J. Exp. Psychol.: Hum. Percept. Perform.* 3:299–315

Squires, N. K., Squires, K. C., Hillyard, S. A. 1975. Two varieties of long-latency positive waves evoked by unpredictable auditory stimuli. *Electroencephalogr. Clin. Neurophysiol.* 38:387–401

Starr, A. 1978. Sensory evoked potentials in clinical disorders of the nervous system. *Ann. Rev. Neurosci.* 1:103–27

Stuss, D. T., Sarazin, F., Leech, E., Picton, T. W. 1982. Evoked potentials during naming. In *Event-Related Potentials in Man*, ed. R. Karrer, P. Tueting, J. Cohen. New York: NY Acad. Sci. In press

Thatcher, R. W. 1977. Evoked potential correlates of hemispheric lateralization during semantic information processing. In *Lateralization of the Nervous System*, ed. S. Harnad, R. W. Doty, L. Goldstein, J. Jaynes, G. Krauthamer, pp. 429–48. New York: Academic

Towey, J., Rist, F., Hakerem, G., Ruchkin, D. S., Sutton, S. 1980. N250 Latency and decision time. *Bull. Psychon. Soc.* 15:365–68

Treisman, A. M. 1969. Strategies and models of selective attention. *Psychol. Rev.* 76:282–99

Treisman, A. M., Gelade, G. 1980. A feature-integration theory of attention. *Cogn. Psychol.* 12:97–136

Treisman, A., Squire, R., Green, J. 1974. Semantic processing in dichotic listening? A replication. *Mem. Cognit.* 2:641–46

Tueting, P. 1978. Event-related potentials, cognitive events, and information processing. See Otto 1978, pp. 159–69

Van Voorhis, S. T., Hillyard, S. A. 1977. Visual evoked potentials and selective attention to points in space. *Percept. Psychophys.* 22:54–62

Velasco, M., Velasco, F., Olvera, A. 1980. Effect of task relevance and selective attention on components of cortical and subcortical evoked potentials in man. *Electroencephalogr. Clin. Neurophysiol.* 48:377–86

Warren, L. R., Marsh, G. R. 1979. Changes in event related potentials during processing of Stroop stimuli. *Int. J. Neurosci.* 9:217–23

Wastell, D. G., Kleinman, D. 1980. Evoked potential correlates of visual selective attention. *Acta Psychol.* 46:129–40

Wilkinson, R. T., Seales, D. M. 1978. EEG, event-related potentials and signal detection. *Biol. Psychol.* 7:13–28

Wood, C. C. 1975. Auditory and phonetic levels of processing in speech perception: Neurophysiological and information-processing analysis. *J. Exp. Psychol.* 104:3–20

Woods, D. L., Courchesne, E., Hillyard, S. A., Galambos, R. 1980. Recovery cycles of event-related potentials in multiple detection tasks. *Electroencephalogr. Clin. Neurophysiol.* 50:335–47

Woods, D. L., Hillyard, S. A. 1978. Attention at the cocktail party: Brainstem evoked responses reveal no peripheral gating. See Otto 1978, pp. 230–33