5

Review of Event-Related Potential Studies of Memory

Marta Kutas

It is no easy matter to describe our conscious experience of memory in either psychological or physiological terms. No doubt, part of the difficulty stems from our inability to observe memory operations in action. It is my aim here to show that some relevant evidence can be provided by investigating the electrical activity of the brain generated when our memories are presented and tested under certain experimental conditions.

5.1 *Event-Related Brain Potentials*

In 1929 Hans Berger, a German psychiatrist, demonstrated that he could monitor some of the electrochemical signals by which brain cells communicate with each other with relative ease. He did so by placing two large pads soaked in saline on the front and back of a person's head and amplifying the voltage difference between them; he referred to these voltage oscillations as the electrical record of the brain (that is, the *elektrenkephalogramm,* or EEG). Although he was unable to turn this finding into a theory of the neural basis of mentation, Berger was successful in showing that the frequency content of the EEG changed with mental activity, such as reading or arithmetic, relative to periods of rest. Today more sophisticated analyses of the relation between information processing and EEG in the frequency domain are complemented by studies of brain waves in the time domain. For example, it is possible to examine voltage fluctuations that are synchronized (time-locked) to a stimulus, response, or event in the environment; these are called evoked potentials (EPs) or event-related potentials (ERPs). The term "event-related" has been adopted because it subsumes both potentials that are evoked by an external stimulus and potentials that are not evoked but instead are elicited by an event. Events may include the absence of an expected stimulus (for example, omitted stimulus response), preparation to take in information (for example, contingent negative variation), and preparation to initiate and perform a movement (for example, the *bereitschafts* or readiness potential). However, although a single ERP is easy to elicit, its characteristics are not as easy to decipher without specialized, computerized techniques. This is primarily because a single ERP is small relative to the co-occurring unsynchronized background EEG and can be masked by larger potentials, such as those associated with body and eye movements and changes in skin resistance (influenced by sweating).

In the normal adult the mean amplitude of an evoked response (10 μV) may be as small as one-tenth the amplitude of the background EEG (100 μV). This signal-to-noise problem typically is remedied by calculating an average of the brain's responses across repetitions of an evoking stimulus or an eliciting event. The utility of the averaging procedure is based on the assumption that the evoked response to a stimulus is the same on each repetition whereas the background EEG is not; thus the random activity cancels, and a consistent response or signal emerges. There are clearly violations of this assumption that show that some ERP components and background activity are correlated (Pritchard et al. 1985; Jasiukaitis, in press). Nonetheless, on occasion, this assumption can be relaxed so that ERPs to more natural stimulation can be investigated. For example, much of "cognitive" ERP research utilizes the repetition of stimuli that are conceptually rather than physically identical. This is particularly true of language research, in which it has proven unnecessary to repeat the same word again and again in order to obtain an average. Rather, it has been possible to average across experimentally defined categories, such as words that follow from the preceding context versus those that do not [for a review, see Kutas and Van Petten (in press) and Rugg et al. (1986)].

Cognitive ERP research is a subclass of EP research that includes studies in which variations in ERP components are related to variations in cognitive processes. Some ERP researchers in this class hypothesize about the functional organization of the brain for certain processes on the basis of interactions between the scalp distribution of the associated ERP components and experimental variables. Others use the ERP as a measure of a cognitive process in much the same way as some behavioral psychologists use reaction time. To some extent these particular ways of utilizing ERP in the study of human cognition are dictated by the fact that, at present, the generators of most ERPs are unknown. However, it is an empirical question as to whether the knowledge of the source of an ERP component will reveal much about its functional significance.

It is generally believed that ERP activity seen at the scalp is the summation of graded postsynaptic potentials (PSPs) generated by the depolarization and hyperpolarization of brain cells; these can be either excitatory (EPSPs) or inhibitory (IPSPs). Several factors—including the number, location, orientation, and synaptic connectivity of the neural elements involved, the location of the recording electrodes, and the properties of the electrically conductive medium—are crucial determinants of the extracellular potentials that are recorded in any particular case (Allison et al. 1986). Because a potential of a given polarity at the scalp can represent depolarization generated locally or hyperpolarization generated at a distance or vice versa, the polarity of a potential per se cannot be used to infer its neurophysiological basis. Moreover, given that extracellular potentials from different sources overlap in time and space according to the principle of superposition, it is not possible to determine either the number or the location of active sources from surface ERP recordings alone.

Nonetheless many ERP researchers do make tentative inferences about the source of a component from its distribution on the scalp. Because this approach is successful on occasion, it is a reasonable first step if neuropsychological, behavioral, and field potential principles are taken into account. For example, there is good correspondence between the distribution of movement-related potentials and the organization of the motor cortex (Vaughan et al. 1968). In contrast, the scalp distribution of the auditory evoked potential (AEP) reveals little about its source; the AEP is largest on top of the head at the vertex, not over the auditory cortex as would be expected from anatomical considerations alone. However, potential field theory predicts that many potentials with generators in each cerebral hemisphere appear largest at the midline locations on top of the head. For reasons such as this, hypotheses about ERP source localization need to be evaluated in light of converging evidence from many disciplines.

One approach that has been adopted recently by those interested in localizing the ERP generators of potentials such as brain stem evoked responses (BERs) and auditory N1 or P3 components has been that of "informed" modeling. The general idea has been to develop a model composed of the fewest number of equivalent dipoles that will account for the scalp potential fields obtained under a specified set of circumstances and then to test this model with real ERP data. The choice of dipoles is influenced by anatomical, neuropsychological, and potential field considerations. Thus far the modelers have restricted themselves to early or exogenous ERPs; however, the concept should apply equally well to later or endogenous ERP components (Scherg and von Cramon 1985a,b; Wood 1982).

Yet another approach to source localization has been to examine ERPs from patients with circumscribed brain lesions. Of course, such lesion data are subject to all the usual criticisms leveled against interpretations about brain functions from lesions. In addition, the interpretation of ERP changes, at least in some patients, is complicated by changes in conductance resulting from skull defects or scar tissue (Nunez 1981). Nonetheless, ERP investigations of brain-damaged individuals have led to some interesting and testable hypotheses regarding the source of various ERP components and, in turn, about the perceptual and cognitive processes they underlie (Knight et al. 1981; Neville et al. 1979; Johnson and Fedio 1984; Knight 1984; Wood et al. 1984; Wood et al. 1982; Stapleton et al. 1987).

Recently, several ERP investigators have suggested that ERP localization from scalp distributions could benefit from detailed mappings utilizing as many electrodes as possible (32–50 being a good starting range). Numerous recording sites have, in fact, been utilized by those researchers who have recorded ERP activity in the depths of the brain. In so doing, they have been able to show that there are characteristic patterns of depth ERP activity coincident with particular scalp-recorded potentials. Certain regions of the brain are characterized by high-amplitude activity, and in some cases potentials change or reverse polarity at what are presumed to be borders of anatomical structures.

Given that depth recordings are generally obtained from the brains of epileptics, albeit from the "normal" side, there has been a remarkable consistency of findings for the P3 component, the most heavily investigated potential thus far (Halgren et al. 1980; Wood et al. 1980). Specifically, several laboratories have observed that a P3-like component undergoes polarity inversion in the hippocampal-amygdala region. Nevertheless it has proven extremely difficult to equate the intracerebral recordings of P3-like activity with the scalp-recorded activity [see Halgren et al. (1986) for criteria necessary for generator identification]. In fact, the consensus from depth recordings of the P3 in humans is that the scalp-recorded activity does not appear to be generated in one place, such as the amygdala or hippocampus, but seems to receive contributions from several regions, including the medial temporal and frontal lobes and probably other brain areas yet unexplored. Data from normal monkeys and monkeys with lesions of the hippocampus and amygdala are consistent with this tentative conclusion (Paller et al. 1982, 1984; Paller 1986).

It may well be the case that, on occasion, neither the source of a cognitive process nor that of its ERP signature will be found in a single distinct anatomical locus. Rather, the processing transactions for any given cognitive event may be distributed at synaptic junctions throughout the brain, and it is the sum or envelope of this widespread activity that is reflected in the ERPs we record. This is a likely possibility whether the ERPs reflect the postsynaptic activity of neurons carrying specific information about events or the action of diffuse modulatory systems [see Pineda (1987) for evidence on the role of the locus ceruleus on P3 generation and Halgren and Smith (1987) for similar thoughts along these lines]. It has been claimed that many of the brain's functions are best modeled by systems that are parallel and functionally distributed (see chapter 4 in this volume). For processes for which this is an apt description, the morphology and coherence among ERPs recorded in various places throughout the depths may be useful in delineating the elements of such distributed functional units. Similar analyses can be applied to reveal relationships among scalp-recorded ERPs (Gevins et al. 1985).

In any case, lack of knowledge or agreement on the anatomical sources of a component need not detract from its utility. Several early (less than 100 msec) EP measures are used daily by neurologists to test the integrity of the central nervous system and by audiologists to determine hearing thresholds in infants and other difficult-to-test individuals (Halliday 1982). In a similar manner, despite our lack of knowledge about their generators, information about various cognitive processes can be gleaned from the potentials occurring later (greater than 50–100 msec).

ERPs and Cognitive Processes

Although an in-depth review of ERPs in cognition is outside the scope of this chapter, a few general remarks are in order. [For detailed reviews, see Gaillard and Ritter (1983), Hillyard and Kutas (1983), and Karrer et al. (1984).] Cognitive ERP researchers have attacked many problems within developmental, experimental, and cognitive psychology. The questions they have posed have been essentially the same as those asked by cognitive scientists or neuroscientists using other dependent measures. In addition, cognitive ERP researchers have examined the timing of the processes under study and/or hypothesized about the brain areas that might be involved in their execution.

The following are but a small sample of the types of questions that have been asked by various cognitive ERP researchers: What system or process is facilitated when we find that reaction times are speeded by a prior cue (Duncan-Johnson and Donchin 1982)? Is a serial stage, a cascade, a continuous flow model, etc. the most appropriate for describing how certain tasks are carried out (Coles et al. 1985)? How many tasks can we perform simultaneously (Wickens et al. 1983;

Wickens 1984)? How is the functional organization of the brain altered by early experience (Neville and Lawson 1987)? What role does prior context play in the comprehension of a single word (Kutas and Hillyard 1980)? What are the mechanisms by which we turn our attention to some items and ignore others (Hansen and Hillyard 1983)? Which aspects of attentional deployment are under conscious control and which are not (Naatanen 1982)? What makes some events more memorable than others (Sanquist et al. 1980)? How similar are processes of recognition and recall (Paller et al. 1987)? What areas of the brain are involved in the formation and retrieval of episodic memories (Halgren and Smith, 1987)?

Although many of these are the same questions that an experimenter collecting reaction times might ask, there is ample data suggesting that ERPs and reaction times do not measure the same underlying processes. In some cases ERP and reaction time measures are highly correlated; however, there are circumstances under which they are not (Friedman et al. 1978; Kutas et al. 1977; Ritter et al. 1979; Brookhuis et al. 1981). This is to be expected to the extent that the processes indexed by reaction times and ERP components only partially overlap. For example, most of the evidence on the relationship between the P3 and the reaction time indicates that P3 latency reflects primarily the nonmotor subset of the processes that determine behavioral reaction times. In fact, it is the possibility that ERPs allow access to processes that are relatively impenetrable with traditional behavioral measures that makes them particularly appealing tools for investigating human cognition and memory, despite their cost (Regan 1972). In addition, ERPs provide a means of viewing the neuroanatomical basis of various cognitive processes in functional rather than purely connectionist ("static") terms.

5.2 *ERPs and Memory*

Some data relevant to our understanding of memory have come from ERP studies conducted outside the explicit domain of memory research. This is not surprising given that some aspect of every process must engage either a memory operation or utilize a memory store. Take, for example, the most basic memories that are programmed into our genes (DNA) and manifested in the anatomical, biochemical, and physiological organization of our brains. These organizations at different levels define the limits of the substrates within which our future memories are formed (Galambos and Hillyard 1981). Moreover, there is ample evidence demonstrating that these prewired connections in the human brain are indeed altered by experience.

In a series of elegant studies Neville demonstrated that ERPs are a useful physiological tool in investigations of early experiences on brain development. She combined behavioral and ERP approaches to show that early auditory deprivation (that is, congenital deafness) modifies the functional organization of both sensory and language systems in the human brain. For instance, she found that the refractory periods of the N1-P2 components of the ERPs elicited by simple light flashes were different in normally hearing and congenitally deaf adults, but only for stimuli presented outside the fovea (Neville et al. 1983). Thus congenital deafness altered the time course of the "physiologic memory" of at least a subset of the neurons involved in the processing of stimuli in the visual periphery. Specifically, the N1 generators in the deaf returned to "normal" functioning after rapid stimulation more quickly than they did in normally hearing individuals. Such a finding implies that the deaf ought to have either greater sensitivity or more efficient intake of peripheral visual stimuli. In fact, the results of a subsequent study showed that congenitally deaf individuals were better than hearing ones at detecting infrequent occurrences of apparent motion in the periphery (Neville and Lawson 1987). Thus it appears that ERPs are sensitive indexes of the functional organization of the brain and changes therein—processes that encompass a large part of the brain bases of learning and memory (in my opinion).

Perhaps another type of "memory" (although I view them as the same) is reflected by the brain changes that occur when a person learns to ride a bicycle or use a typewriter. Procedural memories such as these include the store(s) of skill-based information that is acquired by doing and, in turn, accessed through performance (Squire 1982). It is possible to record ERPs during skill acquisition and to assess corresponding changes in their morphologies, scalp distributions, or other parameters. So far, however, only a few ERP studies have examined changes in movement-related potentials recorded from the human scalp with the acquisition of a motor skill (Taylor 1978) or even during learning of paired associates (Horst et al. 1980) or concepts (Stuss and Picton 1978). Future studies with normal and memory-impaired individuals may reveal much about the laying down of procedural memories (for example, the extent to which procedural learning and traces are lateralized and/or involve different brain regions during acquisition) that are not easily accessible by other currently available methodologies.

As with most behavioral investigations, most ERP studies of memory have dealt with the formation and retrieval of episodic memories. That is, they have been designed to probe the nature of the processes engaged when a subject recognizes or recalls one or more items presented during an experimental episode. The majority of these studies have been concerned with memory for the contents of the items presented (declarative memory). Although rarely noted, I believe it is important to keep in mind that such tests almost invariably involve the language system, whereas similar memories outside the laboratory environment, as well as many tests of "procedural" memory, need not. In the following sections I review studies of short- and long-term memory using the ERP method.

ERPs are sensitive indicators of both physical and categorical changes in the environment. In fact, many of the best-studied ERP components have been described as responses to change or deviation from a train of prior stimuli. In some cases this response to change is considered to be conscious, whereas in others it is unconscious or involuntary. In either case, an appreciation of change requires memory for or some trace of the immediate past. The notion that some cognitive ERP is elicited as a direct or indirect consequence of comparing the eliciting stimulus to a preexisting trace or template plays at least a small part in almost every description of psychological processes underlying various cognitive ERP components. For example, Naatanen (1982) mentions templates in his discussion of several of the ERP components recorded during selective attention paradigms. Similarly Squires et al. (1976) based their theory of the P3b on a decaying "trace" of the stimuli. Similar proposals in terms of orienting and match/mismatch have been offered for the P3a, frontal P3, N2, and N400 components. Insofar as each of these potentials can be associated with more specific cognitive processes or modulation thereof, the body of knowledge on the nature and organization of memories in the human brain will be advanced.

ERP Studies of Recognition and Recall: Short-Term Memory

Since the early 1970s several cognitive ERP researchers have conducted experiments with the expressed purpose of finding out more about memory. All of these investigations were carried out within the context of a particular theoretical view of the memory process under study. In most cases both the hypothetical models of memory being tested and the experimental paradigms used in the testing were borrowed from the domain of experimental psychology. A good example is the Sternberg memory scanning paradigm (Sternberg 1969).

In a typical trial from a Sternberg experiment, a subject is presented with a memory set of 1 to *N* items followed shortly by a probe, target, or test item to which the subject must respond as quickly as possible with one of two buttons. One response indicates recognition of the probe as a member of the original memory set and the other the decision that it was not. Sternberg argued that, by manipulating the number of items in the memory set and measuring the response latency [that is, the reaction time (RT)] to the probe, it was possible to estimate the speed of the search process through short-term memory. He modeled performance in this task using a four-stage serial model composed of (1) stimulus encoding, (2) serial comparison, (3) binary decision, and (4) response organization and execution. Sternberg proposed that the intercept of the function relating probe RT to memory set size was an estimate of the time needed to perform all but the serial comparison stage and that the slope of the RT–memory set size function was an estimate of the time needed to search through memory and scan each item.

Sternberg argued that separate processing stages were empirically justifiable to the extent that one could find experimental variables that affected only one processing stage and did not interact with variables affecting the other processing stages. Although such variables as stimulus legibility, size of positive set, response type, and relative frequency of response type were identified for each of the proposed processing stages, respectively, RT measures did not provide a means for determining the relative durations of the stimulus encoding, decision, and response execution stages (that is, to fractionate the zero intercept time of the RT–memory set size function).

It is just such an analytic problem that the ERP approach in combination with RT measures can overcome. Specifically, it has been proposed that various ERPs, such as the N2 and P3 components, can be used to *estimate* the timing and duration of the component processes that underlie reaction times. The most heavily investigated ERP in this regard has been a positive component variously referred to as the P3, P3b, P300, and LPC. The P3 is a wave of positive polarity at the scalp (relative to an ear, mastoid, or noncephalic reference), with maximum amplitudes at midline centroparietal locations.

P3's can be obtained in a wide variety of tasks [for a review, see Pritchard (1981) and Sutton and Ruchkin (1984)]. Within most of these tasks, P3 amplitude is most sensitive to the subjective probability of stimulus categories and task relevance: The more relevant and the less probable a given stimulus class, the larger the P3 elicited [see Fabiani et al. (1988) and Johnson (in press)]. Although the original discovery of the P3 showed a positive peak with a mean latency around 300 msec poststimulus onset, it has been shown that P3 peaks may vary in latency between 300 and 1,000 msec, increasing in latency as a function of task complexity (Kutas and Donchin 1978). Although reaction times collected concurrently with the P3 likewise increase as a function of processing complexity, the two measures are not always highly correlated. For example, the P3-RT correlation is appreciably larger under task instructions that emphasize *accuracy* of response than under those that emphasize *speed* of response (Kutas et al. 1977).

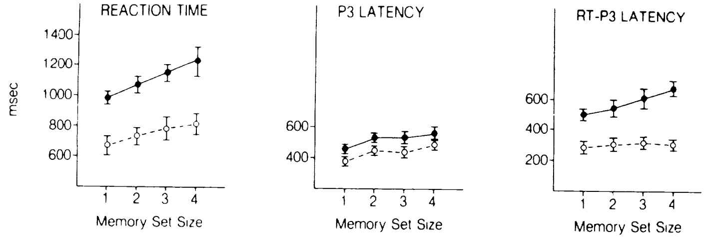
This type of finding led to the proposition that P3 latency and RT are determined by two partially overlapping sets of processes. Subsequent research has been aimed at pinpointing the processes underlying or at least preceding P3 elicitation. Because infrequently occurring stimuli in a categorization task elicit large P3's relative to those elicited by the stimuli in the more frequently occurring category (under certain conditions), Donchin suggested that the latency of the P3 was a *relative marker* of stimulus categorization or evaluation time. Several studies have since indicated that the processes that must be completed before P3's are emitted are related to stimulus evaluation as opposed to response execution. For instance, both stimulus-response compatibility and crossed versus uncrossed hand manipulations had substantial deleterious effects on RT with only minimal effects or no effect on the associated P3's (McCarthy and Donchin 1981; Magliero et al. 1984; Ragot 1984; Mulder et al. 1984). Also consistent with this view of the P3 as reflecting primarily stimulus- as opposed to response-related processing are the findings in which P3's were elicited by infrequent auditory probes in dual-task situations. On the whole these studies showed that P3's to the probes were reduced in amplitude whenever the other task made heavy demands on "perceptual resources" but not when the task demands were predominantly "motor" in nature (Isreal, Chesney et al. 1980; Isreal, Wickens et al. 1980; Wickens and Kessel 1980).

Insofar as this view of P3 and its relation to RT is valid, ERP researchers hoped to combine P3 and RT measures in Sternberg's memory scanning paradigm to get estimates of the duration of each component stage [for another review, see Mulder (1986)]. The initial studies demonstrated that reliable ERP components could be elicited during this task and indicated a tendency for the P3 component to increase in latency with memory set size up to seven items but not beyond (Adam and Collins 1978). Subsequent studies have confirmed this relationship within the visual modality and elaborated the model by fractionating the memory scanning process by means of a series of regressions using P3 latencies and RTs. To reiterate, the working hypothesis is that RT is a composite measure of stimulus evaluation and response processes, whereas P3 latency is an approximate measure of the duration of stimulus evaluation. Within the context of the Sternberg paradigm, P3 latency is presumed to reflect the time necessary for the buildup of evidence about the presence or absence of a target in a visual display (Mulder 1986).

Sternberg's memory scanning model was modified as follows:

1. The slope of the P3 latency–memory set size function rather than that of the RT–memory set size function provides an estimate of serial comparison time.
2. The intercept of this P300 latency function gives an estimate of stimulus encoding time.
3. The interval between the peak of the P300 and the behavioral RT is a measure of the relative timing of response-related processes.
4. The slope of the P300 minus RT function is an estimate of the binary decision time.
5. The intercept of the P300 minus RT function reflects the time taken to translate and organize the response.

Several investigators have applied this modification of Sternberg's model to assess age-related changes in visual memory scanning (Marsh 1975; Ford et al. 1979; Pfefferbaum et al. 1980; Wickens et al. 1987). Although the results are somewhat variable, there are some consistencies [for an in-depth review, see Bashore (in press)]. For example, both RTs and P3 peak latencies are longer in the elderly than in the young. However, although advancing age steepens the slope of the RT–memory set size function, it does not affect the slope of the P3 latency–memory set size function (see figure 5.1). Ford et al. (1980) interpreted these findings to mean that the apparent slowing of memory scanning in the elderly is not due to a mental lapse in their rate of serial comparisons but rather to a moderate decrease in their speed of stimulus encoding and to a significant delay in their response organization and execution. In addition, the results of several studies including concurrent recordings of ERPs and speed-accuracy trade-off assessments in the Sternberg paradigm indicate that the elderly tend to have a more conservative response criterion than the young (Strayer et al., 1987). Bashore also emphasized the importance of differential response strategies in the young and old in accounting for the apparently different effects of age on response latencies as measured by RTs and those measured by peak P3's. Bashore found that, when he regressed the processing latency measures of the elderly onto those of the young across tasks of increasing complexity, as suggested by Cerella (1985), the RT data indicated that age had multiplicative effects, whereas the P3 data indicated that age had additive effects.



	Reaction Time: Slope	Reaction Time: Intercept	P3 Latency: Slope	P3 Latency: Intercept	RT-P3 Latency: Slope	RT-P3 Latency: Intercept
OLD	80 5 msec/digit	905 msec	27 5 msec/digit	444 msec	53 1 msec/digit	460 msec
YOUNG	43 2 msec/digit	645 msec	27 4 msec/digit	373 msec	15 7 msec/digit	271 msec
	t=3 94, p< 05	t=2 86, p< 05	t= 005, n s	t=2 57, p<.05	t=2 79, p< 05	t=2 57, p<.05

Figure 5.1
Means and standard errors for reaction time (RT), P3 latency, and RT-P3 latency as a function of memory set size for old (solid circles and line) and young (open circles and dashed line) subjects. P3 latencies are collapsed across electrode location and response type; RTs are collapsed across response type. Linear equations describing these RT, P3 latency, and RT-P3 latency measures were fitted by the method of least squares. *t*-tests comparing young and old subjects were performed on the slope and intercept data. Below each figure is a table of the slope and intercept of that function for old and young subjects. The value of the *t*-test comparing young and old subjects and an indication of whether it exceeded the $p < 0.05$ level of significance appear below the values of the slopes and intercepts. From Ford et al. (1979).

In conclusion, a cursory examination of the literature dealing with the Sternberg task reveals that Sternberg's original conception of search through short-term memory is neither entirely accurate nor all encompassing (Eriksen and Schultz 1979; McClelland 1979; Meyer et al. 1985). Nonetheless, insofar as the task is used to assess the differential capabilities of two or more experimental groups (as with the young and elderly), it appears as if a combination of ERP and RT measures provides greater precision than does either measure alone. At the least, this combined approach has consistently suggested what may turn out to be a general processing principle of aging, namely, the tendency for the elderly to employ a strategy of opting for accuracy at the expense of speed.

ERPs and Working Memory

The critical role of subject strategy in memory processes has also been highlighted in a series of studies originating from within the ERP research tradition. This line of investigation evolved from the attempts of ERP researchers to determine the consequences of P3 elicitation. The literature on the conditions that give rise to the P3 component is not detailed here [for reviews, see Donchin (1981), Pritchard (1981), and Sutton and Ruchkin (1984)]. Suffice it to say that

Donchin (1981, p. 508) has incorporated much of the available evidence into the proposition that "the P300 is intimately involved with the process of memory modification." Donchin's argument presumes that events are remembered if they require, on their occurrence, a restructuring of mental representations and that it is this process of "context updating" that is reflected in P3 elicitation. Hence one consequence of P3 elicitation is enhanced memorability: Events that elicit a P300 are remembered better than events that do not. Moreover, the larger the P3 elicited by a stimulus, the greater the chance that the stimulus will be remembered. In his most recent formulations, Donchin has argued that context updating is essential to maintain working memory, the temporary storage of information processing. In many respects Donchin's view of working memory converges with that proposed by Baddeley and Hitch (1974) as an alternative to a short-term memory store.

The first attempts by Donchin's group to test his views on the relation between P3 amplitude and memory seemed to go in favor of the Karis et al. hypothesis (Karis et al. 1981). Karis et al. briefly reported the results of two experiments wherein subjects were presented with lists of words, half of which were dim in intensity and half of which were bright. The different conditions included both incidental and intentional memory instructions, responding to only one or both classes of stimuli, and recognition and free recall performance. In general, the results suggested that recalled words were associated with larger P300's on initial presentation than words that were not recalled. However, Karis et al. noted substantial individual variation in the presence and size of this P3 memory effect.

Large individual variability in the relation between P3 amplitude and memory performance was likewise obtained in Karis's next study based on a von Restorff paradigm (von Restorff 1933); however, in this case, they explained these differences in terms of rehearsal and recall strategies. Specifically, Karis et al. (1984) found that all subjects produced large P3's to infrequent occurrences of a word typed in a smaller or larger size (that is, isolates) than the others in the list; however, only the three subjects who reported using a rote rehearsal strategy had larger P300's for words recalled than for words not recalled. The three subjects who reported using elaborative rehearsal techniques (that is, relating list items to each other or to personal experiences and/or world knowledge) elicited P3's of equal amplitude regardless of subsequent memory performance, whereas the results of the six other subjects were intermediate. The group differences were present to all the stimuli, albeit largest for the isolates.

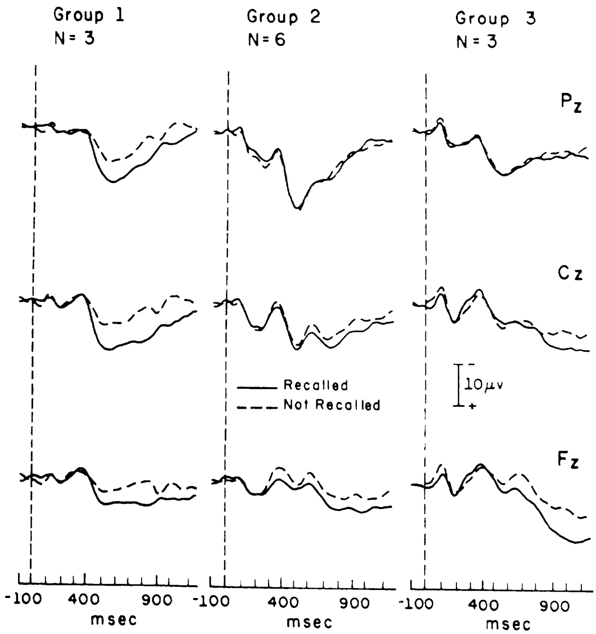


Figure 5.2
Group averages for isolates at three mid-line electrode sites (Fz, frontal; Cz, central; Pz, parietal). Average ERP to words recalled and not recalled are superimposed. Note that members of group 1 are the rote memorizers, and members of group 3 are the elaborators. From Karis et al. (1984).

The two groups differed in other respects as well. As a group the rote memorizers recalled fewer words than did the "elaborators." However, the members of the rote group recalled significantly more of the isolates than other word types, whereas the elaborators remembered about the same percentage of all word types. Finally, although P3 amplitude was not predictive of subsequent recall in the elaborators, a broad, positive "slow wave" with a frontal distribution was (see figure 5.2).

This proposed interaction among P3 amplitude, memory, and subject's strategy was examined in several subsequent studies by Donchin's group. In one, Fabiani et al. (1986) evaluated the relationship between P3 amplitude and subsequent recall under conditions in which the recall test was incidental to the subject's instructed task of counting male or female names. Fabiani et al. assumed that, because the subjects had no reason to expect a recall test, they would not use elaborative strategies to rehearse the stimuli and therefore would show a positive correlation between P3 amplitude and recall. The stimuli consisted of a Bernoulli sequence of male and female names

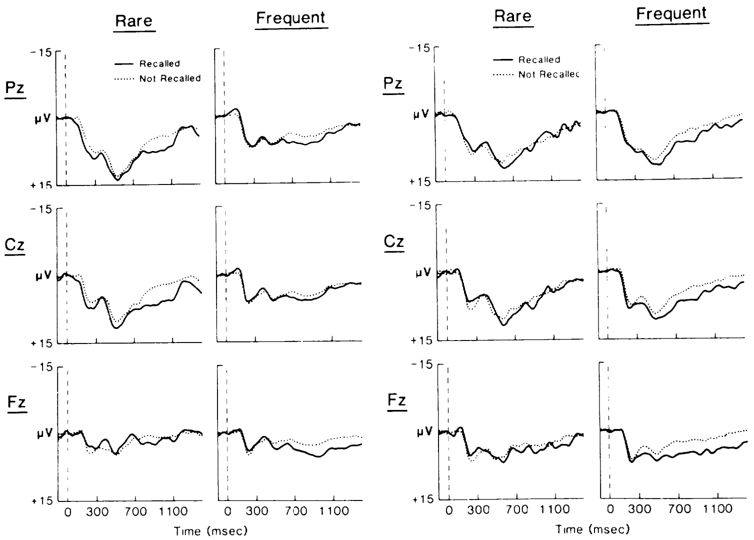


Figure 5.3
(Left) Grand average waveforms from the first block of the name isolate of subjects in the count-rare group (N = 23). Rare names and frequent names were sorted on the basis of their subsequent recall. (Right) Grand average waveforms from the first block of the name isolate of subjects in the count-frequent group (N = 18). Rare names and frequent names were sorted on the basis of their subsequent recall. From Fabiani et al. (1986).

(with no name repeated) occurring in categories with unequal probabilities (20/80 or 80/20). Across subjects, each of the categories occurred with a high or low probability and was or was not counted.

Probably owing to the incidental nature of the memory task, subjects performed very poorly, recalling only 16% of the names presented. It was nonetheless possible to compare ERPs elicited by recalled and not recalled names because of the large number of subjects employed. Visual inspection of the raw waveforms sorted as a function of subsequent recall (note the unequal number of trials in the two categories in figure 5.3) indicates some memory-related differences in these ERP comparisons. In the ERPs elicited by the frequent category, the memory effect is long lasting (400–1,100 msec) and equipotential in amplitude across the scalp, regardless of whether the stimuli were counted or uncounted. In the ERPs elicited by the rare category, the memory effect appears to be later (800–1,100 msec) and centroparietal in distribution and interacts with the counting task (see figure 5.3). The authors discounted these effects by stating that these grand average waveforms included substantial latency variability in the P3 peak.

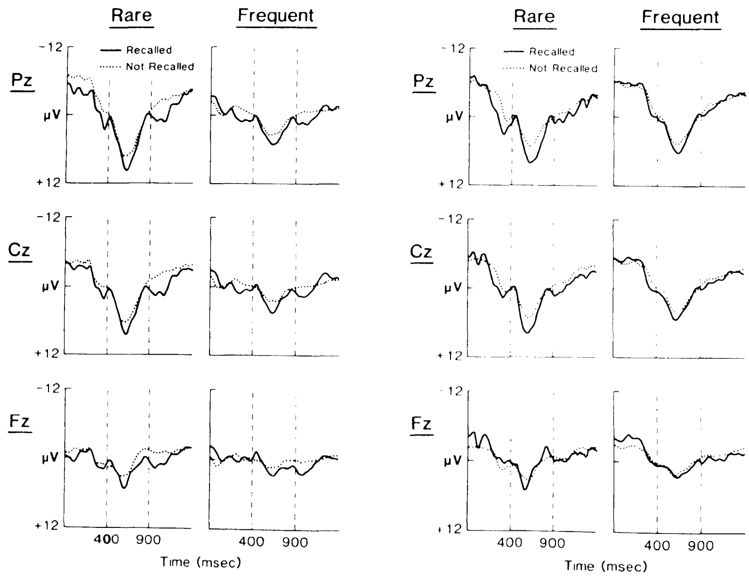


Figure 5.4
(Left) Latency-adjusted grand average waveforms from the first block of the name isolate of subjects in the count-rare group ($N = 23$). Rare names and frequent names were sorted on the basis of their subsequent recall. The two vertical dashed lines indicate the limits of the time window in which P300 was identified. The baseline for the waveforms was taken at the beginning of the window. (Right) Latency-adjusted grand average waveforms from the first block of the name isolate of subjects in the count-frequent group ($N = 18$). Rare names and frequent names were sorted on the basis of their subsequent recall. From Fabiani et al. (1986).

The memory-related ERP effects obtained after the data have been subjected to a latency adjustment procedure are shown in figure 5.4. In this analysis the ERPs elicited by all conditions show a memory effect at the P3 peak, larger for recalled than not recalled names. Across the different experimental conditions and stimulus categories, the distribution of the memory effect varies from equipotential to somewhat parietal; in any case latency adjustment appears to alter not only the peakedness of the late positivities but also their scalp distributions (relative to those of the unadjusted waveforms). In addition, the ERPs elicited by rare names that were counted are characterized by a later memory-related effect. Fabiani et al. (1986) suggested that this effect may be a second P3 after the categorization P3, elicited when the subject relates the name to a known person or song. Moreover, they argued that, in so doing, subjects increase the probability of recall of that word. This proposition was supported by the presence of a second P3 only in the averages of recalled names; however, it is inconsistent with the main proposition that the relation between P3 amplitude and recall is abolished by elaboration. Although Fabiani et al. concluded that these data were evidence of a strong relationship between P300 amplitude and subsequent recall, they did not provide compelling evidence that it was indeed the P3 and only the P3, rather than a temporally overlapping process, that varied with memory.

In the next study in this series, Fabiani et al. (n.d.) directly manipulated subjects' rehearsal strategies by means of instructions in a von Restorff paradigm. Rote memory instructions required subjects to repeat each word as it was presented, whereas elaboration instructions urged subjects to combine words into images, sentences, or stories. Both free recall and size recall were assessed throughout the experiment. The results generally confirmed those obtained in the Karis et al. study; different rehearsal strategies were associated with different patterns of overall recall. Overall recall was better under elaborate than rote strategies. The ERP data likewise replicated the findings of Karis et al.; the relationship between P3 amplitude and subsequent recall was more pronounced under rote than elaborate instructions, whereas the relation between a later ERP effect and recall was present only under elaborate instructions. As in the previous experiment, however, the exact nature (amplitude and scalp distribution) of these memory-related ERP effects appeared to be influenced by the latency adjustment procedure. This is especially important, given that there is some controversy in the literature as to whether it is the P3 per se whose amplitude variation predicts recall (Halgren and Smith 1987; Paller et al. 1987).

Insofar as the concept of working memory underlying Donchin's laboratory research is equivalent to that outlined by Baddeley and Hitch (1974), it may be possible to determine more precisely the cognitive process that the ERP memory effect reflects. Baddeley and Hitch fractionated working memory into at least three subcomponents: a central executive component and two supplementary slave systems (an articulatory loop and a visuospatial scratch pad). The central executor is assumed to be responsible for control processes, the articulatory loop for the maintenance of speech-based material through subvocalization, and the visuospatial store for maintenance of spatially coded information. There is strong evidence supporting the articulatory loop and some controversy as to the need for a visuospatial scratch pad (Phillips and Christie 1977; Baddeley and Lieberman 1980). In any case, although Donchin's group has not identified the P3–working memory relation with any particular aspect of working memory, some preliminary data on this issue was presented during Donchin's presentation at the Eighth International

Conference on Event-Related Slow Potentials of the Brain (EPIC VIII) held in Stanford, California, in June 1986.

As a start, Allison Fox in Michie's laboratory in Australia attempted to replicate Donchin's data on the relations among P3 amplitude, memory, and rehearsal strategy in a von Restorff paradigm. The only obvious difference between her study and that of Fabiani et al. was that Fox controlled subjects' elaborative strategies by instructing them to form visual images. Fox and her colleagues obtained behavioral data in agreement with those of Fabiani et al. Fox's ERP data, likewise, revealed an influence of strategy, although the pattern of effects differed somewhat from those of Donchin's group. Specifically, strategy altered the apparent scalp distribution of the memory-related differences in response to the isolates: Both groups had an effect over the parietal site, whereas the rote memorizers also had an equivalent-size effect at the frontal recording site.

With these findings in hand, Fox made use of the Baddeley model of working memory by combining the von Restorff paradigm and the strategy manipulation with one of two interference tasks, each assumed to engage different aspects of working memory. These tasks were performed on single letters presented one at a time between the words of the von Restorff paradigm. In the verbal interference task subjects were required to decide whether or not the target letter rhymed with the letter "e." In the visual inference task, subjects were asked to image the letter and determine whether or not it contained a curve.

In terms of memory performance both interference tasks were most detrimental under rote memory instructions. As for the ERPs, under rote instructions verbal interference enhanced the difference between recalled and nonrecalled items, whereas visual interference abolished the recall difference. In contrast, under the elaborate instructions verbal interference abolished the ERP recall effect, whereas visual interference enhanced the original parietal effect and revealed one at the frontal site. Although detailed analyses are necessary to determine what these data say about either P3 or Baddeley's model of working memory, these preliminary data are quite promising. There does indeed seem to be some relation between working memory and late component(s) of ERPs that is altered by the nature of rehearsal strategies.

Again, although it is not clear that the observed ERP effects can be attributed to modulation of the P300 component, unequivocally such data bode well for future ERP studies of working memory. At the least, the results of such investigations may offer practical suggestions as to the nature of the tasks that people can perform simultaneously without a drop in processing efficiency and those that will create trouble when performed in unison. Such studies also allow tests of the hypothesized subcomponents of working memory. In addition, these ERP findings suggest that it might be possible to alter the efficacy of dual (and perhaps multiple) task performance by altering people's processing and/or rehearsal strategies.

ERP Indexes of Encoding

Converging evidence for a possible relationship between the formation of memory traces and variation in the amplitude of the ERP in the latency range of the P3 component has come from other quarters of ERP research. In particular, several ERP researchers have looked to see whether any part of the ERP can be a metric of encoding operations within episodic memory. Extrapolating from the findings that ERPs do vary with information processing, these researchers assumed as a working hypothesis that various ERP components might provide indexes of the "unobservable processes, correlated with instructions to the subjects and the subsequent mental activity [that] determine the extent to which the studied material is retained" (Tulving 1983, p. 153). Many of these experiments were conducted within the levels-of-processing framework because it has been one of the more influential encoding-based theories of episodic memory (Craik and Tulving 1975; Craik and Lockhart 1972).

Traditionally cognitive psychologists have assessed the effect of differential encoding on memory by asking subjects to perform different orienting tasks with the same set of materials and comparing their percent correct recognitions or recall across the tasks. The results of such experiments have demonstrated that the nature of the orienting task can have profound effects on the memory scores. For example, under many, although not all, experimental procedures, semantic-level analyses lead to better retention than nonsemantic analyses. Such results have been interpreted to mean that the nature of initial encoding is a major determinant of whether or not an item will be remembered. Among proponents of the levels-of-processing framework of memory such results led to the proposition that memory performance is a function of "depth" of initial encoding. Depth refers to the amount of semantic processing (semanticity) that an item has received, although there is no one measure of semanticity that can be applied across all experimental paradigms.

Given the overwhelming evidence that orienting tasks have such a marked influence on memory performance, it is easy to forget that neither differential encoding nor the link between differential encoding and memory are direct observations. Rather, their existences have been inferred from the effects of task instructions on performance measures obtained minutes or hours after the subject's initial exposure to the material to be remembered. Because the ERP is an online reflection of at least some of the physiological activity of the brain during stimulus encoding, insofar as it can be related to variations in encoding operations, it can be used as a converging measure either to undermine or to reinforce hypotheses about the role of encoding in episodic memory. Thus it has been of some interest to determine how experimental manipulations of encoding are reflected in the ERP and the extent to which such ERP effects correlate with subsequent memory performance. For example, if depth of processing is a viable concept in memory trace formation, it is possible that some ERP parameter might vary systematically with fluctuations in depth and thereby serve to measure it. It is just such a hope that spurred several ERP investigators to record ERPs within typical levels-of-processing paradigms.

Before detailing the results of these studies, I must point out two of the assumptions implicit in using ERPs in this way: (1) ERP waveforms that are similar in morphology reflect the engagement of qualitatively similar processes, whereas those that are different reflect the activity of qualitatively distinct processes; (2) amplitude and latency changes in ERP components reflect quantitative, not qualitative, differences in processing. These working assumptions are based on some general observations that ERP researchers have made over the years. Namely, quantitative manipulations, such as increasing the brightness or the loudness of stimuli, typically lead to larger amplitudes or shorter latencies for the early sensory components of the ERP, whereas a qualitative change, such as a difference in the modality of presentation, yields a qualitatively different set of sensory components. Some cognitive ERP components have been shown to behave in a similar fashion. For example, variations in semantic expectancy are mirrored in quantitative changes in N400 amplitude, whereas deviations from a physical expectancy are associated with a late positive complex (Kutas and Hillyard 1980). Although such simple notions probably do not capture all the complexities of a working brain, working assumptions are easiest to relinquish in the face of direct contradictory evidence rather than theoretical possibilities.

Sanquist et al. (1980) were the first to compare the ERPs collected during three different orienting tasks. The tasks, which necessitated yes/no judgments about two words according to one of three criteria (for example, orthographic similarity, rhyming, and synonymy), were ones that had previously been shown to yield different levels of retention. And indeed Sanquist et al. obtained the expected results:

(1) Semantic judgments led to better subsequent recognition than did rhyme judgments, which in turn led to better recognition than judgments about the case (upper or lower) in which the two words were printed. (2) In addition, "same" judgments were followed by better recognition than were "different" judgments for the phonemic and semantic but not orthographic conditions.

Likewise the ERP data indicated an interaction between the orienting task and the type of judgment (for example, same or different): The ERPs elicited by "same" judgments were quite similar across all three tasks, whereas those elicited by "different" judgments were not (see figure 5.5). Specifically, "same" judgment ERPs were characterized by a late positivity whose duration increased steadily from the orthographic to the semantic task. On the other hand, "different" judgment ERPs were characterized by a large negativity (around 400 msec) in the semantic task, a moderate-size negativity in the phonemic task, and positivity with a negative notch in the orthographic task.

If these waveform differences are interpreted as previously discussed, then one conclusion would be that the processing of same and different items differs qualitatively in at least one operation. By contrast, the processing differences among the three orienting tasks seems to be quantitative rather than qualitative in nature. These ERP patterns are thus inconsistent with the view that the different orienting tasks invariably engage qualitatively distinct operations. The decision to respond "same" appears to involve similar encoding operations regardless of the linguistic dimension along which the judgments are being made, whereas the decision to respond "different" appears to call on qualitatively different encoding operations for semantic versus other types of processing. The varying durations of the late positivity in association with "same" responses across tasks probably reflects quantitative differences in the use of a particular cognitive process, the psychological identity of which remains uncertain at present. In any case the data patterns converge with behavioral data, suggesting that no simple concept such as depth of encoding is likely to explain the differential memory performance across these particular tasks [reviewed in Tulving (1983)]. At the least, another variable is necessary to account for the different encoding required by "same" versus "different" judgments in the phonemic and semantic tasks.

The Sanquist et al. data might have revealed more about the relationships among ERP parameters, encoding, and memory performance if it had allowed comparisons among the ERPs elicited during each of the orienting tasks, averaged as a function of subsequent

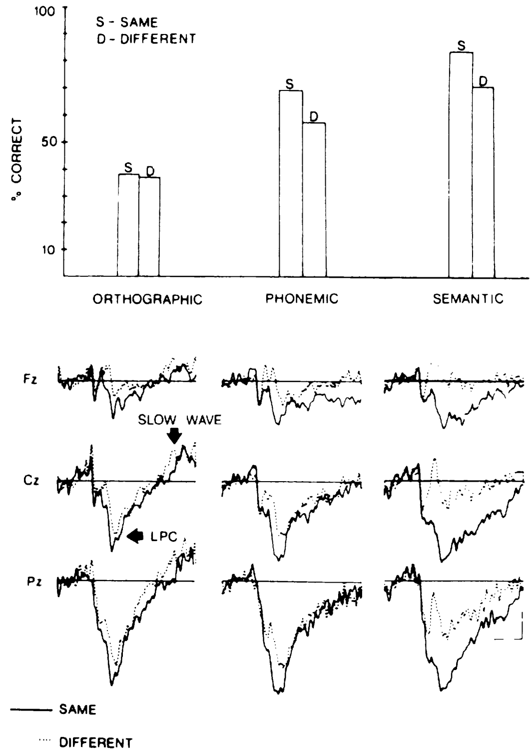


Figure 5.5
Percent correct recognition for each comparison criterion and judgment type. Shown below each comparison criterion are the grand average ERPs elicited by the second word in a pair for that condition. ERPs were digitized at the rate of 102.4 samples per second for a 2,500-msec epoch. Stimulus onset occurred following a 500-msec baseline. Calibrations: 500 msec and 5 μV, negativity upward. From Sanquist et al. (1980).

recognition performance and same/different judgments. Unfortunately there were not enough trials to generate all the subaverages necessary to make these comparisons. To the extent that this comparison was carried out (for example, for the semantic task ERPs), the data implied different encodings for items that would or would not be subsequently recognized. However, it is impossible to say this with certainty because the recognized/unrecognized comparison was confounded with the same/different judgment, in that subjects recognized many more "same" than "different" words. On the other hand, if this ERP pattern was not due to the confounding with response type, then it suggests substantial overlap between the encoding of "same" items that will not be recognized and those judged to be "different" (at least in the semantic domain).

Another ERP study (Paller et al., 1987) conducted within the levels-of-processing tradition included a sufficient number of trials to allow comparisons among the ERPs elicited during initial encoding as a function of subsequent recognition in both semantic and nonsemantic orienting tasks. These comparisons revealed that the type of memory-related ERP effect observed by Sanquist et al. appears to be more robust in semantic as opposed to nonsemantic tasks (although there is a possibility of a "floor effect" confound in the nonsemantic tasks).

By including two nominally semantic (for example, "Is it living?" or "Is it edible?") and two nominally nonsemantic tasks (for example, "Are there exactly two vowels?" or "Are the first and last letters in alphabetical order?"), Paller et al. also were able to assess the generality of their findings. In so doing, they found that it was an oversimplification to assume that processing during two semantic or two nonsemantic tasks were equivalent by virtue of their being deemed so by the experimenter. The ERPs elicited by the two semantic tasks and those elicited by the two nonsemantic tasks differ either in morphology or distribution over the scalp (see figure 5.6). By inference, so did at least some of the neural and perceptual and cognitive processing underlying the different tasks.

Moreover, whereas neither nonsemantic task elicited a significant memory-related ERP effect, one was associated with a large late positivity and the other was not. Thus Paller et al. concluded that the memory-related ERP effect could be dissociated from the P3. This finding, together with the observation that the ERP differences based on subsequent recognition and recall have a scalp distribution different from that of the typical P3 component, further suggested that the two ERP effects are independent. Of course, under some experimental conditions the P3 component might still vary in amplitude with

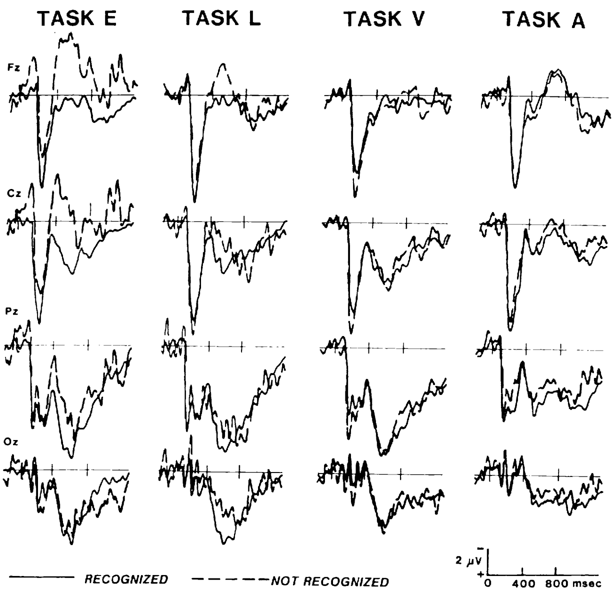


Figure 5.6
Grand average ERPs associated with each processing task; averaged based on later recognition performance. Note the ERP difference between words later recognized (solid lines) and words not recognized (dashed line) was greater in the two semantic task, especially task E. From Paller et al. (1987).

some aspect of memory. However, Paller et al.'s results imply that attributing variation in a late positivity to variation in the P3 component per se be done with great care [also see Halgren and Smith (1987)].

Finally, Paller et al. observed that the ERP signs of subsequent recognition during initial encoding are similar regardless of the nature of task decision (that is, yes or no). Items followed by a "yes" response did, however, evoke a slightly larger late ERP difference between subsequently recognized and unrecognized items than those followed by a "no" response. On the average, items associated with "yes" decisions were better recognized than those associated with "no" decisions. Perhaps some combination of the reduced priming (reflected in larger negativity) and decreased "additional" processing (reflected in less of a memory-related enhancement in the positivity) could account for the worse recognition of "no" items.

This set of observations may be important because it is the inability of the original levels-of-processing framework to account for the differential memorability of items associated with yes/no, same/different, or congruent/incongruent responses, especially within the semantic domain, that led to its reformulation. Within the revision, differential elaboration was invoked to account for the observation that congruent items are better remembered than incongruous ones (Craik and Jacoby 1979). For example, Craik and Tulving (1975) suggested that the congruity between a context and a target allowed the formation of an integrated memory unit that, once formed, could be elaborated, whereas incongruous context-target pairings did not, thus producing the observed differences in their retention. It is unclear whether this explanation implies that elaboration is a part of the encoding process or an adjunct to it. Moreover, this description provides no information about the time course of elaboration, if such a unitary process exists. Furthermore, the invocation of the "congruity" variable implies that there may be a special relationship between episodic memory and the rich store of preformed associations embodied in one's knowledge and experience with a language.

Interactions of Semantic and Episodic Memory

It was within the context of such questions that Neville et al. (1986) decided to use the ERP to examine the relationship between initial processing and subsequent memory. In particular, they wanted to determine how and when semantic congruity and elaboration contributed to episodic memory trace formation and recognition. This line of research drew on a relatively established ERP measure of semantic congruity. It has been found that during silent reading the differential processing of words that fit a given context and those that do not is apparent in the visual ERP within 200 msec of a word's presentation. Semantically incongruous or anomalous words within a sentence elicit ERPs characterized by a large negative component peaking around 400 msec (N400), whereas highly predictable, congruous endings elicit ERPs with a positive peak around 350 msec (Kutas and Hillyard 1980). The results of several investigations aimed at validating the N400 as a measure of semantic processing have led to the working hypothesis that N400 may be an index of semantic expectancy (Kutas and Hillyard 1984; Kutas et al. 1984). In these studies semantic expectancy was defined operationally in terms of cloze probability (Taylor 1953). However, in my view the semantic expectancy of an item is a function of a multitude of factors (automatic and under attentional control) that heighten the activation of particular semantic concepts relative to others. Lexical associations, the frequency of usage of a word in the language, grammatical, semantic, thematic, and pragmatic constraints, etc. may under certain circumstances contribute to a word's semantic expectancy. To date, it has been found that N400 amplitude bears an inverse relationship to behavioral measures of semantic priming; priming, in this case, refers to the increased speed or efficiency of processing of an item following a semantically related one relative to its following an unrelated item (Bentin et al. 1985; Fischler et al. 1983). Thus knowledge of the relations between congruity and recognition memory, between congruity and the N400, and between subsequent memory and the ERP was combined in the hopes of leading to a better understanding of why semantic incongruity results in poor memory performance.

Both experiments reported by Neville et al. (1986) obtained the typical N400 effect, namely, greater negativity in association with words that do not fit a preceding context (for example, type of weapon–sheep) than in association with words that do fit (for example, A type of insect–ant). Shortly after the initial presentation subjects were asked to differentiate the "old" words (sheep, ant) presented in isolation from their original context from an equal number of "new" words. Both studies replicated the common behavioral finding of better recognition for words that were congruous than those that were incongruous. Thus to some extent there was an inverse correlation between the average size of the N400 wave elicited by a word and the likelihood that it would be recognized in a test. However, the data clearly demonstrated that congruity per se (as reflected in N400 amplitude) could not account for memory performance singlehandedly. Incongruous words elicited N400's of equivalent amplitudes whether or not they were subsequently recognized. In fact, the ERPs elicited by incongruous words showed no effect of recognition until 500 msec or so (that is, past the N400 peak); the processes involved in recognition memory appeared to influence the amplitude of a late, broad positivity (P650). Likewise the responses to congruous words displayed a greater positivity for the to-be-recognized words (see figure 5.7). Whether the reduced positivity to congruous words that would not be recognized was due to variation solely in the amplitude of the late positivity or to the presence of an enhanced N400 could not be determined. However, congruent items that will not be recognized do seem to elicit a modest-sized N400.

Several aspects of these data are quite informative. First, we can note that the brain's response to each congruous word is not fully determined by the experimenter's classification of the stimuli. If the decreased N400 elicited by some congruous items (relative to incongruous items) reflects the fulfillment of a semantic expectancy, then clearly not all congruous items are equally expected. Because Neville et al. did not attempt to equate the degree of semantic expectancy among the congruous items, fluctuation in this variable may have accounted for the differential recognition and ERP responses within

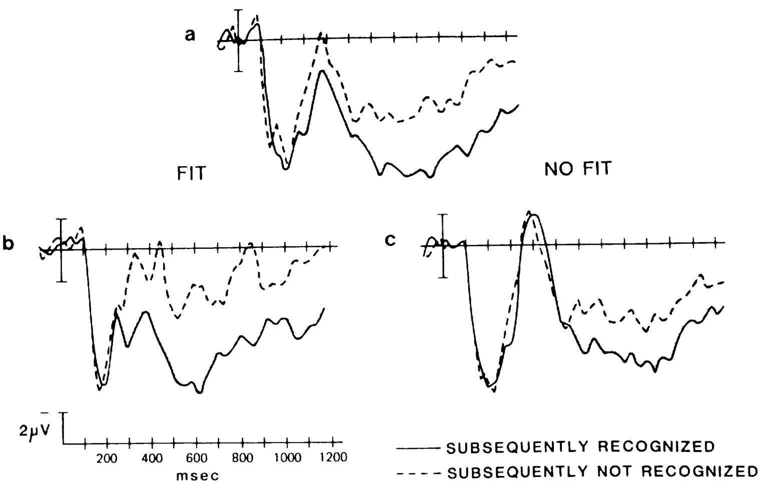


Figure 5.7
ERPs recorded from Cz in the judgment task of Experiment 2 averaged according to subsequent recognition in the recognition test. (a) ERPs averaged across fit and no-fit words. (b) ERPs averaged for fit words and (c) no-fit words. Solid line, subsequently recognized; dashed line, subsequently not recognized. From Neville et al. (1986).

the set of congruent words. However, it is also possible that these differences reflect individual variation in unconscious semantic priming or in the attention paid to the preceding phrase, which was supposed to set up the expectancy. In any case these data suggest that it is not objective congruity per se but rather degree of semantic expectancy or priming that accounts for the enhanced recognition of congruous relative to incongruous words. An alternative view also consistent with these data would say that the amplitude of the N400 elicited by a particular word is related to the number of elements in the lexicon that were activated to some degree in an attempt to interpret the word given the context. A large N400 would indicate some minimal activation of many lexical items (possibly "logogens") in the search for meaning. In this view incongruous words are difficult to remember because their activations do not differ from those of the numerous other words that received some activation.

At present, it is unclear what other processes involved in the formation of the memory traces for congruous words are reflected in the ERP waveforms. Neville et al. proposed that the enhanced positivity following the N400 was associated with increased elaborative processing; however, other candidates have not been ruled out. In any case the ERP data suggest that this same process also was invoked during the analysis of incongruous words, albeit to a lesser degree and with a delayed onset. It appears as if semantic priming might hasten the onset of this additional encoding process, thereby enhancing the subsequent recognizability of the primed word. This proposition assumes that semantic priming aids in the formation and storage of episodic memories by taking advantage of the existing organization of semantic memory.

I examined these issues in a subsequent experiment in which I analyzed the ERPs elicited by congruous and incongruous endings sorted as a function of recall. After reading 160 sentences for content, subjects were asked to recall the final word of each sentence on receiving all but the final word as a cue. It was important to determine whether or not cued recall would result in ERP patterns similar to that for recognition; such data were necessary before generalizations about the underlying mechanisms could be made. Moreover, the proposed hypothesis that semantic priming was involved in episodic retention needed to be tested. If semantic priming was instrumental in episodic memory, then incongruous sentence endings that were somehow related to the expected completions ("The game was called when it started to umbrella.") should be recalled better than incongruous endings that were not so related ("George was fired but he could not tell his fog."). This prediction was based on a previous observation (Kutas et al. 1984) that related incongruities ("umbrella") elicited smaller N400's than unrelated incongruities ("fog").

As predicted, when cued with a sentence fragment, not only was recall better for congruous (68%) than incongruous sentences but semantically related incongruities were recalled significantly more often than unrelated incongruities (41% versus 7%). The ERP data likewise showed the expected pattern: positivity in response to congruous endings, large N400's to unrelated semantic anomalies, and somewhat smaller N400's to semantically related anomalies. In addition, related incongruities elicited a late positive component over the front of the head that was not evident in response to unrelated anomalies. Sorting these initial responses as a function of recall revealed a pattern of differences quite similar to that previously obtained for recognition (see figure 5.8). On average, greater priming (as reflected in smaller N400's) indicated better recall regardless of congruity, although words with equal amplitude N400's could be associated with different recall performance. In addition, ERP signs of recall appeared to be earlier and more robust for congruous than incongruous endings.

All of the ERP data discussed are consistent with the hypothesis that there is substantial overlap between the operations involved in comprehension and those involved in the formation of episodic mem-

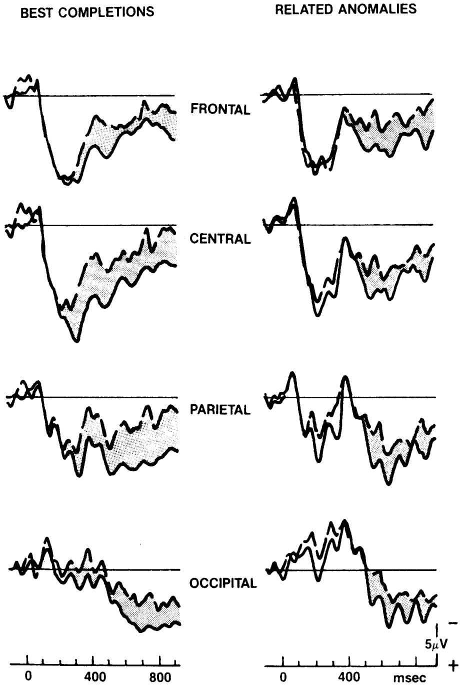


Figure 5.8
Grand average (ERPs) elicited by comparisons of congruous ("best completions") and incongruous ("related anomalies") during initial encoding averaged as a function of subsequent recall. Solid line, subsequently recalled; dashed line, subsequently not recalled.

ory traces for verbal materials. This proposed overlap reflects the intimate use of semantic memory during episodic memory trace formation. The similarity of semantic and episodic memory mechanisms also has been discussed by other ERP investigators (Fischler et al. 1984; Halgren and Smith, in press). Semantic priming (measured by means of increased RTs or decreased N400 amplitudes) and aspects of repetition priming (not discussed here) are presumed to be a consequence of the efficient use of the structure of semantic memory. In this view semantic priming aids memory by affording the to-be-remembered item access to an organized semantic memory, thereby leading to greater ease of comprehension and storage. A strong test of this idea, however, must await the results of memory experiments in which episodic and semantic relationships are dissociated [such as in the RT experiments of Neely (1977)]. Nonetheless the ERP data suggest that semantic expectancy exerts at least some of its influence on the processing and retention of a word within half a second of its initial encoding, not just during the memory test. Similar conclusions can be drawn about the role of familiarity on recognition memory on the basis of ERP experiments not reviewed here [see, for example, Johnson et al. (1985), Smith et al. (1986), and Halgren and Smith (1987) for the role of the medial temporal lobe in such processes].

These data converge with others in suggesting that comprehension aids memory (Bransford et al. 1977). Accordingly one means of improving retention is to improve comprehension. The ERP data further suggest that the context in which an idea is presented has a significant impact on its comprehensibility. A context that can draw on existing mental schema and/or an existing network of semantic associations generally leads to quicker and greater understanding than one that cannot make use of well-traveled pathways in semantic memory. Practically, "new" items are best taught (that is, learned and remembered) in the context of what is already known, although it is also important to note the features of the new item that distinguish it from the old.

5.3 *Practical Conclusions*

Because ERPs can, in theory, provide an online assessment of a subset of the brain processes at any given moment, regardless of their accessibility to conscious awareness, they might seem to be an excellent way of tracking memory operations in the brain. In theory they are. However, before ERPs can be so used online in a training situation, it is essential to determine their sensitivity to hypothetical memory processes and/or performance variables. That is, it is necessary to validate the proposed relationships between any ERP parameter and any memory process. This is no small task. Years of research have shown that memory is not a unitary concept (witness the proliferation of memory terminology). Moreover, demonstrating a reliable and valid relationship may be difficult for the very reason that ERPs are useful, namely, because they reflect the activity of multiple processes, at least some of which are outside of awareness and therefore cannot be discussed, although they may nonetheless have behavioral consequences.

The main thrust of this chapter has been a review of the ERP studies that have been designed to validate relationships between various ERP parameters and memory processes. Much of this work has revolved around use of the P3 component of the ERP to study what has been variously called short-term or working memory. At one level the results of these experiments have converged with data from other disciplines in demonstrating that working memory is

1. Limited in capacity (<7 bits).
2. Takes time to search (30–45 msec per item).
3. Consists of more than one subcomponent (for example, "central executor" + articulatory loop + possibly "visuospatial scratch pad").

The results indicate that these various subcomponents of working memory are differentially utilized by subjects, with the difference being one of strategy. There is also evidence that a subject's natural strategy can be altered according to the desired behavioral outcome. If overall recall is the desired goal, then "elaboration" is the preferred strategy. On the other hand, if certain items need to be remembered at the expense of others, then rote memorization is the strategy of choice.

In addition, P3 studies of working memory have suggested that slowed search through the short-term store of information is not invariably attributable to slowing of mental processes. For example, the elderly seem to have relatively normal mental scanning rates but are slower in performing a scanning task because they tend to be cautious about responding and slower at controlling their musculature. A similar combined ERP-RT approach could be directed at assessing the effects of number of important variables (stress, lack of sleep, noisy environment, number of simultaneous tasks that need to be performed, etc.) not only on performance but on the speed of stimulus evaluation. Perhaps slowing in different processing or execution stages could be remedied by different training algorithms. For example, if ERP assessment revealed that stress acts to retard motor output but not to scramble the underlying mental processes, it might be possible to alter the required behavioral response so that it is less susceptible to fluctuations in muscle control.

The bulk of the remaining research on ERPs and memory has dealt with the role of encoding in episodic memory trace formation and retrieval. To date, ERP data have highlighted the critical roles of semantic priming and comprehension in episodic memories, but the role of other factors remains to be assessed. For example, it should be possible to examine the encoding and performance consequences of stimulus repetition or different modes of practice (for example, massed versus spaced) to determine which factors truly act during encoding and which have their impact during a subsequent process such as consolidation or during retrieval. Moreover, by using ERP technology across verbal units larger than the word (averaging across sentences or sentence fragments), researchers can assess the time course of recognition or recall. Finally, such analyses will allow tracking some of the brain processes involved in memory operations for which people are behaviorally amnestic, namely, those that cannot be consciously accessed. However, it is important to remember that these advances occur during the testing of theories of memory developed in a basic research environment and that the outcome of the tests can be no better than the theories they were designed to test.

Acknowledgments

Some of the work reported here has been supported by the National Science Foundation under grant BNS 83-09243, the National Institute of Neurological and Communicative Disorders and Stroke under grant NS 17778, and the National Institute of Child Health and Human Development under grant HD 22614. M. Kutas is supported by an RCDA Award from the National Institutes of Mental Health (MH 00322). Special thanks to C. Van Petten, K. A. Paller, and S. A. Hillyard for their editorial comments on previous versions of this manuscript.

References

Adam, N., and G. I. Collins. 1978. "Late components of the visual evoked potential to search in short-term memory." *Electroencephalography and Clinical Neurophysiology* 44:147–156.

Allison, T., C. C. Wood, and G. McCarthy. 1986. "The central nervous system," in *Psychophysiology, Systems, Processes, and Applications,* M. G. H. Coles, E. Donchin, and S. W. Porges, eds. New York: Guilford Press, 5–25.

Baddeley, A. D., and G. J. Hitch. 1974. "Working memory," in *Recent Advances in Learning and Motivation,* G. Bower, ed. New York: Academic Press, vol. 8.

Baddeley, A. D., and K. Lieberman. 1980. "Spatial working memory," in *Attention and Performance VIII,* R. S. Nickerson, ed. Hillsdale, N.J.: Erlbaum Associates, 521–539.

Bashore, T. R., A. Osman, and E. H. Heffley. 1988. "Mental slowing in the elderly: A cognitive psychophysiological analysis." Unpublished.

Bentin, S., G. McCarthy, and C. C. Wood. 1985. "Event-related potentials, lexical decision and semantic priming." *Electroencephalography and Clinical Neurophysiology* 60:343–355.

Berger, H. 1929. "Uber das Elektrenkephalogramm des Menschen." *Archiv für Psychiatrie Nervenkrankheiten* 87:527–570.

Bransford, J. D., N. S. McCarrell, J. J. Franks, and K. E. Nitsch. 1977. "Coming to understand things we could not previously understand," in *Perceiving, Acting and Knowing: Toward an Ecological Psychology,* R. E. Shaw and J. D. Bransford, eds. Hillsdale, N.J.: Erlbaum Associates, 431–466.

Brookhuis, K. A., G. Mulder, L. J. M. Mulder, A. B. M. Mulder, H. J. Gloerich, J. J. Van Dellen, J. J. Van der Meere, and H. Ellerman. 1981. "Late positive components and stimulus evaluation time." *Biological Psychology* 13:107–123.

Cerella, J. 1985. "Information processing rates in the elderly." *Psychological Bulletin* 98:67–83.

Coles, M. G. H., G. Gratton, T. R. Bashore, C. W. Eriksen, and E. Donchin. 1985. "A psychophysiological investigation of the continuous flow model of human information processing." *Journal of Experimental Psychology: Human Perception and Performance* 11:529–553.

Craik, F. I. M., and L. L. Jacoby. 1979. "Elaboration and distinctiveness in episodic memory," in *Perspectives on Memory Research: Essays in Honor of Uppsala University's 500th Anniversary*, L.-G. Nilsson, ed. Hillsdale, N.J.: Erlbaum Associates, 145–166.

Craik, F. I. M., and R. S. Lockhart. 1972. "Levels of processing: A framework for memory research." *Journal of Verbal Learning and Verbal Behavior* 11:671–684.

Craik, F. I. M., and E. Tulving. 1975. "Depth of processing and the retention of words in episodic memory." *Journal of Experimental Psychology: General* 104:268–294.

Donchin, E. 1981. "Surprise! . . . Surprise?" *Psychophysiology* 18:493–513.

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

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

Fabiani, M., D. Karis, and E. Donchin. 1986. "P300 and recall in an incidental memory paradigm." *Psychophysiology* 23:298–308.

Fabiani, M., D. Karis, and E. Donchin. n.d. "The effects of mnemonic strategy manipulation in a von Restorff paradigm." Unpublished.

Fabiani, M., G. Gratton, D. Karis, and E. Donchin. 1988. "The definition, identification, and reliability of measurement of the P300 component of the event-related brain potential," in *Advances in Psychophysiology*, P. K. Ackles, J. R. Jennings, and M. G. H. Coles, eds. Greenwich, Conn.: JAI Press, vol. 2.

Fischler, I., P. A. Bloom, D. G. Childers, A. A. Arroyo, and N. W. Perry, Jr. 1984. "Brain potentials during sentence verification: Late negativity and long-term memory strength." *Neuropsychologia* 22:559–568.

Fischler, I., P. A. Bloom, D. A. Childers, S. E. Roucos, and N. W. Perry, Jr. 1983. "Potentials related to sentence verification." *Psychophysiology* 20:400–409.

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

Friedman, D., H. G. Vaughan, Jr., and L. Erlenmeyer-Kimling. 1978. "Stimulus and response related components of the late positive complex in a visual discrimination task." *Electroencephalography and Clinical Neurophysiology* 45:319–330.

Gaillard, A. W. K., and W. Ritter, eds. 1983. *Tutorials in Event-Related Potential Research: Endogenous Components*. Amsterdam: North-Holland.

Galambos, R., and S. Hillyard. 1981. "Electrophysiological approaches to human cognitive processing." *Neurosciences Research Program Bulletin* 20:141–265.

Gevins, A. S., J. C. Doyle , B. A. Cutillo, R. E. Schaffer, R. S. Tannehill, and S. L. Bressler. 1985. "Neurocognitive pattern analysis of a visuospatial task: Rapidly shifting foci of evoked correlations between electrodes." *Psychophysiology* 22:32–43.

Halgren, E., and M. E. Smith. 1987. "Cognitive evoked potentials as modulatory processes in human memory formation and retrieval." *Human Neurobiology* 6:129–140.

Halgren, E., J. M. Stapleton, M. Smith, and I. Altafullah. 1986. "Generators of the human scalp P3(S)," in *Frontiers of Clinical Neuroscience. Vol. 3, Evoked Potentials*, R. Q. Cracco and I. Bodis-Wollner, eds. New York: Alan R. Liss, 269–286.

Halgren, E., N. K. Squires, C. L. Wilson, J. W. Rohrbaugh, T. L. Babb, and P. H. Crandall. 1980. "Endogenous potentials generated in the human hippocampal formation and amygdala by infrequent events." *Science* 210:803–805.

Halliday, A. M., ed. 1982. *Evoked Potentials in Clinical Testing*. Edinburgh: Churchill Livingstone.

Hansen, J. C., and S. A. Hillyard. 1983. "Selective attention to multidimensional auditory stimuli in man." *Journal of Experimental Psychology: Human Perception Performance* 9:1–19.

Hillyard, S. A., and M. Kutas. 1983. "Electrophysiology of cognitive processing." *Annual Review of Psychology* 34:33–61.

Horst, R. L., R. Johnson, Jr., and E. Donchin. 1980. "Event-related brain potentials and subjective probability in a learning task." *Memory and Cognition* 8:476–488.

Isreal, J. B., G. L. Chesney, C. D. Wickens, and E. Donchin. 1980. "P300 and tracking difficulty: Evidence for multiple resources in dual-task performance." *Psychophysiology* 17:259–273.

Isreal, J. B., C. D. Wickens, G. L. Chesney, and E. Donchin. 1980. "The event-related brain potential as an index of display-monitoring workload." *Human Factors* 22:211–224.

Jasiukaitis, P. In press. "The effect of pre-stimulus alpha activity on the P300." *Psychophysiology.*

Johnson, R. E., Jr. In press. "The amplitude of the P300 component of the event-related potential: Review and synthesis," in *Advances in Psychophysiology,* P. K. Ackles, J. R. Jennings, and M. G. H. Coles, eds. Greenwich, Conn.: JAI Press, vol. 3.

Johnson, R. E., Jr., and P. Fedio. 1984. "ERP and P300 activity in patients following unilateral temporal lobectomy." *Society for Neuroscience Abstracts* 10:847.

Johnson, R. E., Jr., A. Pfefferbaum, and B. S. Kopell. 1985. "P300 and long-term memory: Latency predicts recognition performance." *Psychophysiology* 22:497–507.

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

Karis, D., T. Bashore, M. Fabiani, and E. Donchin. 1981. "P300 and memory." *Psychophysiology* 19:328.

Karrer, R., J. Cohen, and P. Tueting, eds. 1984. *Brain and Information: Event-Related Potentials.* New York: New York Academy of Sciences.

Knight, R. T. 1984. "Decreased response to novel stimuli after prefrontal lesions in man." *Electroencephalography and Clinical Neurophysiology* 59:9–20.

Knight, R. T., S. A. Hillyard, D. L. Woods, and H. J. Neville. 1981. "The effects of frontal cortex lesions on event-related potentials during auditory selective attention." *Electroencephalography and Clinical Neurophysiology* 52:571–582.

Kutas, M., and E. Donchin. 1978. "Variations in the latency of P300 as a function of variations in semantic categorization," in *New Perspectives in Event-Related Potential Research,* D. Otto, ed. Washington, D.C.: US Environmental Protection Agency, 198–201.

Kutas, M., and S. A. Hillyard. 1980. "Reading senseless sentences: Brain potentials reflect semantic incongruity." *Science* 207:203–205.

Kutas, M., and S. A. Hillyard. 1984. "Brain potentials during reading reflect word expectancy and semantic association." *Nature* 307:161–163.

Kutas, M., and C. Van Petten. In press. "Event-related brain potential studies of language," in *Advances in Psychophysiology,* P. K. Ackles, J. R. Jennings, and M. G. H. Coles, eds. Greenwich, Conn.: JAI Press.

Kutas, M., T. Lindamood, and S. A. Hillyard. 1984. "Word expectancy and event-related brain potentials during sentence processing," in *Preparatory States and Processes,* S. Kornblum and J. Requin, eds. Hillsdale, N.J.: Erlbaum Associates, 217–237.

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

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

McClelland, J. L. 1979. "On time relations of mental processes: A framework for analyzing processes in cascade." *Psychological Review* 86:287–330.

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

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

Meyer, D., S. Yantis, A. M. Osman, and J. E. K. Smith. 1985. "Temporal properties of human information processing: Tests of discrete versus continuous models." *Cognitive Psychology* 17:445–518.

Mulder, G. 1986. "Memory search paradigms and practice effects," in *Cognitive Psychophysiology: Studies in ERPs*, W. C. McCallum, R. Zappolli, and F. Denoth, eds. Amsterdam: Elsevier, 57–63.

Mulder, G., A. B. M. Gloerich, K. A. Brookhuis, H. J. van Dellen, and L. J. M. Mulder. 1984. "Stage analysis of the reaction time process using brain-event related potentials and reaction time." *Psychological Review* 46:15–32.

Naatanen, R. 1982. "Processing negativity: Evoked-potential reflection of selective attention." *Psychological Bulletin* 92:605–640.

Neely, J. H. 1977. "Semantic priming and retrieval from lexical memory: Roles of inhibitionless spreading activation and limited-capacity attention." *Journal of Experimental Psychology: General* 106:226–254.

Neville, H. J., and D. Lawson. 1987. "Attention to central and peripheral visual space in a movement detection task II. Congenitally deaf adults." *Brain Research* 405:268–283.

Neville, H. J., M. Kutas, and A. Schmidt. 1982. "Event-related potential studies of cerebral specialization during reading II. Studies of congenitally deaf adults." *Brain and Language* 16:316–337.

Neville, H. J., A. Schmidt, and M. Kutas. 1983. "Altered visual-evoked potentials in congenitally deaf adults." *Brain Research* 266:127–132.

Neville, H. J., M. Kutas, G. Chesney, and A. Schmidt. 1986. "Event-related brain potentials during the initial encoding and subsequent recognition memory of congruous and incongruous words." *Journal of Memory and Language* 25:75–92.

Neville, H. J., E. Snyder, R. Knight, and R. Galambos. 1979. "Event-related potentials in language and non-language tasks in patients with alexia without agraphia," in *Human Evoked Potentials Applications and Problems*, D. Lehmann and E. Callaway, eds. New York: Plenum Press, 269–283.

Neville, H. J., E. Snyder, D. Woods, and R. Galambos. 1982. "Recognition and surprise alter the human visual evoked response." *Proceedings of the National Academy of Sciences USA* 79:2121–2123.

Nunez, P. L. 1981. *Electric Fields of the Brain*. New York: Oxford University Press.

Paller, K. A. 1986. "Effects of medial temporal lobectomy in monkeys on brain potentials related to memory." Ph.D. dissertation. University of California, San Diego. Unpublished.

Paller, K. A., M. Kutas, and A. Mayes. 1987. "Neural correlates of encoding in an incidental learning paradigm." *Electroencephalography and Clinical Neurophysiology* 67:360–371.

Paller, K. A., S. Zola-Morgan, L. R. Squire, and S. A. Hillyard. 1982. "Late positive event-related potentials in cynomolgus monkeys (*Macaca fasicularis*)." *Society for Neuroscience Abstracts* 8:975.

Paller, K. A., S. Zola-Morgan, L. R. Squire, and S. A. Hillyard. 1984. "Monkeys with lesions of hippocampus and amygdala exhibit event-related brain potentials that resemble the human P300 wave." *Society for Neuroscience Abstracts* 10:849.

Pfefferbaum, A., J. M. Ford, W. T. Roth, and B. S. Kopell. 1980. "Age differences in P3-reaction time associations." *Electroencephalography and Clinical Neurophysiology* 49:257–265.

Phillips, W. A., and D. F. M. Christie. 1977. "Components of visual memory." *Quarterly Journal of Experimental Psychology* 29:117–133.

Pineda, J. 1987. "Endogenous event-related potentials in nonhuman primates: The role of the noradrenergic locus coeruleus system." Ph.D. dissertation. University of California, San Diego. Unpublished.

Pritchard, W. S. 1981. "Psychophysiology of P300: A review." *Psychological Bulletin* 89:506–540.

Pritchard, W. S., M. E. Brandt, S. A. Shappell, T. J. O'Dell, and E. S. Barratt. 1985. "P300 amplitude/pre-stimulus EEG power relationships." *Psychophysiology* 22:609–610.

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

Regan, D. 1972. *Evoked Potentials in Psychology, Sensory Physiology, and Clinical Medicine.* London: Chapman and Hall.

Restorff, H. von. 1933. "Uber die Wirkung von Bereichsbildungen im Spurenfeld." *Psycholigische Forschung* 18:299–342.

Ritter, W., R. Simson, H. G. Vaughan, and D. Friedman. 1979. "A brain event related to the making of a sensory discrimination." *Science* 203:1358–1361.

Rugg, M., A. Kok, G. Barrett, and I. Fischler. 1986. "ERPs associated with language and hemispheric specialization: A review," in *Cognitive Psychophysiology: Studies in ERPs,* W. C. McCallum, R. Zappolli, and F. Denoth, eds. Amsterdam: Elsevier, 273–300.

Sanquist, T. F., J. W. Rohrbaugh, K. Syndulko, and D. B. Lindsley. 1980. "Electrocortical signs of levels of processing: Perceptual analysis and recognition memory." *Psychophysiology* 17:568–576.

Scherg, M., and D. von Cramon. 1985a. "A new interpretation of the generators of BAEP waves I–V: Results of a spatio-temporal dipole model." *Electroencephalography and Clinical Neurophysiology* 62:290–299.

Scherg, M., and D. von Cramon. 1985b. "Two bilateral sources of the late AEP as identified by a spatio-temporal dipole model." *Electroencephalography and Clinical Neurophysiology* 62:32–44.

Smith, M. C., L. Theodor, and P. E. Franklin. 1983. "The relationship between contextual facilitation and depth of processing." *Journal of Experimental Psychology: Learning, Memory and Cognition* 9:697–712.

Smith, M. E., J. M. Stapleton, and E. Halgren. 1986. "Human medial temporal lobe potentials evoked in memory and language tasks." *Electroencephalography and Clinical Neurophysiology* 63:145–159.

Squire, L. 1982. "The neuropsychology of human memory." *Annual Review of Neuroscience* 5:241–273.

Squires, K., C. Wickens, N. Squires, and E. Donchin. 1976. "The effect of stimulus sequence on the waveform of the cortical event-related potential." *Science* 193:1142–1146.

Stapleton, J. M., E. Halgren, and K. A. Moreno. 1987. "Endogenous potentials after anterior temporal lobectomy. *Neuropsychologia* 25:549–557.

Sternberg, S. 1969a. "The discovery of processing stages: Extensions of Donders' method." *Acta Psychologica* 30:276–315.

Sternberg, S. 1969b. "Memory-scanning: Mental processes revealed by reaction-time experiments." *American Scientist* 57:421–457.

Strayer, D. L., C. D. Wickens, and R. Braune. 1987. Adult age differences in the speed and capacity of information processing II. An electrophysiological approach." *Psychology and Aging* 2(2):99–110.

Stuss, D. T., and T. W. Picton. 1978. "Neurophysiological correlates of human concept formation." *Behavioral Biology* 23:135–162.

Sutton, S., and D. S. Ruchkin. 1984. "The late positive complex: Advances and new problems," in *Brain and Information: Event-Related Potentials,* R. Karrer, J. Cohen, and P. Tueting, eds. New York: New York Academy of Sciences, 1–23.

Taylor, M. 1978. "*Bereitschaftspotential* during the acquisition of a skilled motor task." *Electroencephalography and Clinical Neurophysiology* 45:568–576.

Taylor, W. L. 1953. " 'Cloze' procedure: A new tool for measuring readability." *Journalism Quarterly* 30:415.

Tulving, E. 1983. *Elements of Episodic Memory.* Oxford: Clarendon Press.

Vaughan, H. G., Jr., L. D. Costa, and W. Ritter. 1968. "Topography of the human motor potential." *Electroencephalography and Clinical Neurophysiology* 25:1–10.

Wickens, C. D. 1984. "Processing resources in attention," in *Varieties of Attention,* R. Parasuraman and D. R. Davies, eds. London: Academic Press, 63–102.

Wickens, C. D., and C. Kessel. 1980. "The processing resource demands of failure in dynamic systems. *Journal of Experimental Psychology: Human Perception and Performance* 6:564–577.

Wickens, C. D., R. Braune, and A. Stokes. 1987. "Age differences in the speed and capacity of information processing I: A dual task." *Psychology and Aging* 2(2):70–78.

Wickens, C., A. Kramer, L. Vanasse, and E. Donchin. 1983. "Performance of concurrent tasks: A psychological analysis of the reciprocity of information-processing resources." *Science* 221:1080–1082.

Wood, C. C. 1982. "Application of dipole localization methods to source identification of human evoked potentials." *Annals of the New York Academy of Sciences* 388:113–135.

Wood, C. C., T. Allison, W. R. Goff, P. D. Williamson, and D. D. Spencer. 1980. "On the neural origin of P300 in man." *Progress in Brain Research* 54:51–56.

Wood, C. C., G. McCarthy, T. Allison, W. R. Goff, P. D. Wiliamson, and D. D. Spencer. 1982. "Endogenous event-related potentials following temporal lobe excisions in humans." *Society for Neuroscience Abstracts* 8:976.

Wood, C. C., G. McCarthy, N. K. Squires, H. G. Vaughan, D. L. Woods, and W. C. McCallum. 1984. "Anatomical and physiological substrates of event-related potentials: Two case studies," in *Brain and Information: Event-related Potentials,* R. Karrer, J. Cohen, and P. Tueting, eds. New York: New York Academy of Sciences, 681–721.