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FROM SINGLE-CHANNEL RECORDINGS TO BRAIN-MAPPING DEVICES:
The Impact of Electroencephalography on Experimental Psychology

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Since its discovery in 1929, the electroencephalogram (EEG) has become a widely used tool in experimental psychology. Although originally the merits of the method were seen first of all in an improvement of medical diagnostics it was soon understood by psychologists that the EEG can also be used to study psychic processes in healthy participants. This article summarizes important events in the history of EEG research that laid the ground for this development, as fast Fourier transformation to analyze the spontaneous activity and signal averaging to improve the signal-to-noise ratio. The article shows how general technological developments were the prerequisite for these methodological improvements in EEG research and how they inspired new research questions. Key discoveries that proved unequivocally that psychic processes do become manifest in EEG signals are briefly reviewed, and the emerging paradigm of cognitive psychophysiology, which is closely linked to the development of EEG research, is described.

Nowadays, the electroencephalogram (EEG) has become a widely used tool in experimental psychology. Almost every psychological department in the United States and in western Europe (in particular, in Great Britain, France, The Netherlands, and Germany) has at least one EEG laboratory, which is most often the only prestigious piece of equipment to be shown to visitors. Journals, originally devoted to behavioral measurements only, publish an increasing number of articles in which EEG signals are used as dependent variables—for example, the *Journal of Experimental Psychology, Memory and Language*—and other journals, such as *Cognitive Brain Research* and *Psychophysiology,* dedicate more than 50% of their space to psychological EEG studies. Why has the EEG become such a success, and why are psychologists, whose main interest is behavior and subjective experience, so keen on using the EEG to study mental processes and brain–behavior relationships? There are many other biological signals that, at a first glance, might be as good as the EEG in helping to find answers to psychological questions—skin conductance changes, the electromyogram, cardiovascular changes, and so forth—and for which biobehavioral relationships have been discovered as well (Rösler, 2000) but, nevertheless, the EEG is the most widely used biosignal. In this article I try to find some answers to these questions. To this end, I briefly outline some of the historical roots of the method and try to show how particular technological developments were the prerequisites for progress in using the EEG as a research tool in experimental psychology.

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The Beginnings: Noninvasive EEG Recordings, Spectral Analysis, and Arousal

Although the phenomenon of brain electrical activity was discovered in 1875 by an English surgeon (Caton, 1875), the merit of recording brain electrical activity from the unopened skull belongs without any doubt to Hans Berger (Berger, 1929). Berger was a psychiatrist at the University of Jena, Germany. He had experimented with highly sensitive radio amplifiers to record electrical activity from the unopened skull. First he had experimented with patients with trepanations due to surgical or accidental reasons, but soon he discovered that a good signal could also be recorded from the unopened skull of healthy subjects. He named the phenomenon *Elektrenkephalogramm*.

For signal recording, Berger used very large plate electrodes—first made from lead and later from silver—that were placed over the forehead and the occipital part of the skull. One of his first recordings is shown in Figure 1. Berger was very skeptical at the beginning and well aware of the possibility that these signals could be artifacts. Therefore, he recorded a number of additional signals already better understood at that time—for example, the electrocardiogram—to prove that the signal picked up from the scalp was genuinely generated in the head and not just an artifact of other physiological processes. He ran other control studies to exclude the influence of breathing or movement activity. Eventually he was convinced that the signal originated from the nervous system, and he published his observations in a series of 14 articles, "Mitteilungen über das Elektrenkephalogramm [Reports on the Electroencephalogram]," between 1929 and 1938. A final overview article appeared in the honorable *Nova Acta Leopoldina* 1938 (Berger, 1938). See also Borck (2005) for a more comprehensive account of Berger's pioneering work on the EEG.

From the very beginning, Berger was interested in psychophysiological relationships. In his very first article he mentioned the possibility of an interaction between mind and brain, and in the summary article of 1938 he recapitulated his motivations:

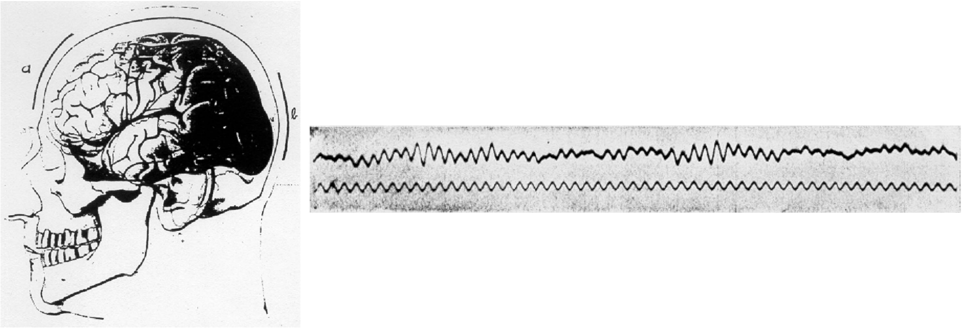

Figure 1. One of the first recordings of an electroencephalogram (EEG). Left panel: schematic illustration of the localization of lead plate electrodes: Right panel, upper trace: EEG of Hans Berger's son Klaus (15 years). Right panel, lower trace: time marker, sine wave 10 Hz. From "Über das Elektrenkephalogramm des Menschen, 1. Mitteilung," by H. Berger, 1929, *Archiv für Psychiatrie*, *87*, p. 553.

> Als ich mich dann dem Studium der Medizin zuwandte, waren es die Erkrankungen des Großhirns und die psychischen Erkrankungen, die mich vor allen Dingen anzogen, weil ich glaubte, da dieser mich besonders beschäftigenden Frage nachgehen zu können. Die *Psychophysiologie*, das Grenzgebiet, in dem sich Physiologie und Psychologie berühren, oder die Wissenschaft, die sich die Aufgabe gesetzt hat, den Zusammenhang, in dem die Hirnvorgänge und die zugehörigen psychischen Vorgänge stehen, im einzelnen genauer festzustellen, das sollte mein Forschungsgebiet werden! [When I eventually started to study medicine, I was primarily attracted by the diseases of the brain and the psychiatric illnesses, because I believed that the question I was most interested in could be pursued in this field at best. It was the discipline of *psychophysiology*, the border area where physiology and psychology meet, which should become my research area—the science which tries to delineate the relationships between brain processes and psychic events.] (Berger, 1938, p. 173; translation by Frank Rösler).

Berger's first systematic observations revealed the basic phenomenology of the EEG, the basic rhythms: alpha—high amplitude regular waves with a frequency around 10 Hz, and beta—small amplitude irregular waves with frequencies higher than 10 Hz. He related these phenomena to general states of activation. Alpha was mainly observed during rest, and beta was usually observed during mental activity, for example, mental calculation.

Berger's discovery was well accepted in the United States, and several laboratories soon started to record brain electrical activity from psychiatric patients and from nonpsychiatric control participants while they were involved in various mental activities (Gibbs, Davis, & Lennox, 1935; Jasper & Carmichael, 1935; Saul & Davis, 1933). It is interesting to notice that Berger was a psychiatrist, that is, a physician, residing in a medical department. This was the normal affiliation for European EEG researchers until the end of World War II. Lord Adrian (1889–1977), winner of the Nobel Prize of physiology in 1932, who was one of the pioneers of EEG research in England (e.g., Adrian & Matthews, 1934), was a physician, too. In the United States, the situation was different. From the very beginning, psychologists were attracted by the EEG. For example, Donald B. Lindsley (1907–2003), a psychologist, pioneered experimental EEG research in its relation to the concept of arousal (Lindsley, 1952). He became the first president of the Central Association of Electroencephalographers and later president of the American EEG Society (1965). Another prominent psychologist who promoted the EEG and other biosignals to study emotion was Chester Darrow (1893–1967; Gullickson, 1973).

A major problem at the beginning of EEG research was the parametrization of the complex signal. Most often, the analysis was done by mere visual inspection. The discovery of sleep stages by Eugene Aserinsky and Nathaniel Kleitman, for example, was achieved by inspection of the EEG and a visual classification of EEG and eye movement activity patterns (Aserinsky & Kleitman, 1953). The most objective method between 1930 and 1950 was to count zero crossings of the signal per time unit by hand. This resulted in rough estimates of the relative expression of slow frequencies. A basic finding established by these methods was that the EEG is systematically related to different states of vigilance. *Arousal* or *activation* were the key constructs. These early findings motivated three lines of research that were systematically pursued by psychologists between 1950 and

1970: studies on the functional relationships between EEG and (a) mental states, either physiologically or psychologically defined (sleep, reading, mental calculation, etc.); (b) personality differences, defined by questionnaires and tests (extraversion, intelligence, etc.); and (c) mental health status, defined by psychiatric and neurologic syndromes (epilepsy, schizophrenia, depression, etc.).

A great step forward to find answers to these questions was the introduction of objective methods of analysis, in particular, spectral analysis of the signal. First, it was performed by analog filter banks, but since the mid-1960s, when computers became available, it has been done with digital computers. The basic idea was to extract the frequency content of the signal in an objective manner. This can be easily achieved by means of the mathematical theorem of Fourier, because each time series $f(t)$ can be described as a superposition of elementary sine and cosine waves (Rösler, 1980, 1996; Walter, 1963):

$$f(t) = a_0 + \sum_{i=1}^{n} a_i \sin(i\,2\pi f_0 t) + \sum_{i=1}^{n} b_i \cos(i\,2\pi f_0 t).$$

In a language that might be more familiar to psychologists, one can see the equation as a multiple regression problem in which the signal $f(t)$, as a criterion, has to be predicted (explained) by a set of elementary sine and cosine waves with frequencies increasing from $i = 1$ to an upper limit of $i = n$. The total set of regression coefficients provide the power spectrum of the signal. They indicate the absolute or relative contribution of the frequencies to the total signal. A prototypical result is shown in Figure 2. Before high-speed computers were available, the route to extract such a power spectrum from a stretch of EEG was stony and demanding. The EEG was recorded on analog magnetic tape and digitized offline on punch tape. The punch tape was fed into a central computer and stored on digital tape. Then sophisticated programs were applied that did the fast Fourier

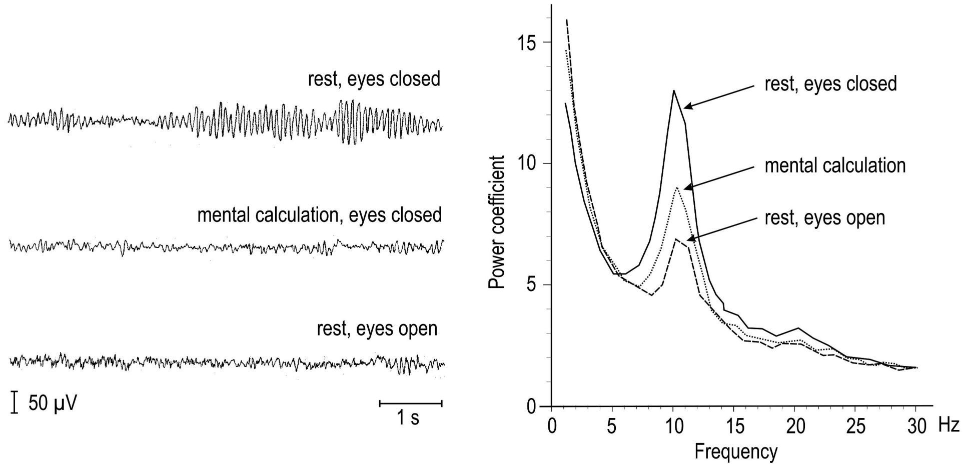

Figure 2. Left panel: spontaneous electroencephalogram (EEG) from three distinct recording situations. Right panel: power spectra of the EEG epochs shown on the left. Based on data from Rösler (1975a).

transform by using not more than 32 KB of core memory—this was the limitation of the computers around 1965; that is, all interim results had to be stored again on magnetic tape. Such an analysis with several epochs of EEG recorded from one scalp site easily took several hours.

By the end of the 1960s, systematic EEG research was established at psychological institutes in Germany and in Austria. Hubert Rohracher (1903–1972), who was primarily interested in microvibration, also studied EEG, and he trained several young people in Vienna who later became leading figures as psychophysiologists and as EEG researchers (Roman Ferstl, Niels Birbaumer, Giselher Guttmann). Gustav Lienert (1920–2001), who was also influenced by Rohracher during his psychology studies in Vienna, installed an EEG machine in 1961 when he was appointed professor of psychology at the Psychology Department of the University of Hamburg. There, he ran some experiments on how psychotropic drugs changed the EEG. This machine was inherited by Lienert's successor in Hamburg, Kurt Pawlik, another scholar of Rohracher. Pawlik had done some EEG work at R. B. Cattell's laboratory at the University of Illinois (Pawlik & Cattell, 1965), and he was mainly interested in activation indices related to personality differences, so-called *objective personality measures*. I myself learned my first steps with the EEG as a student assistant in Kurt Pawlik's laboratory in Hamburg.

Many of the studies conducted at that time by psychologists had a very similar design: The EEG of a sample of subjects was recorded from one or two electrodes in some more or less precisely defined "activation" conditions. The recording interval per experimentally induced state lasted at least a minute, usually longer. I now briefly summarize one study that can be taken as prototypical of the research paradigm. In this study (Rösler, 1975a), the idea was to test the extent to which the EEG was a function of both personality and situation variance. The theoretical background was taken from the work of Eysenck (1967), who had postulated that extraverted and introverted people differ in their arousal level and their susceptibility to arousing environmental challenges. A group of participants was recruited and allotted to four distinct personality groups by a double median split of factor scores of the dimensions introversion (E–)/extraversion (E+) and emotional stability (N–)/neuroticism (N+). This resulted in four groups: (a) E–N–, (b) E+N–, (c) E–N+, and (d) E+N+. The factor scores were derived from a personality test battery, comprising tests such as the 16 Personality Factor Questionnaire (Cattell, Eber, & Tatsuoka, 1970), the German translation of Eysenck's personality questionnaire (ENNR [extraversion, neuroticism, and rigidity]; Brengelmann & Brengelmann, 1960; Eysenck & Eysenck, 1964), and so forth. The participants experienced six situations, each covering an epoch of about 5 min: (a) rest, (b) listening to a story, (c) unexpected noise, (d) rest, (e) mental calculation (easy), and (f) mental calculation with a stress-inducing instruction ("this is an intelligence test"). The EEG was sampled for six epochs distributed over the total time of one situation; each epoch lasted 4 s. The total data set was analyzed with spectral analysis that provided, per subject, 36 power spectra covering the frequencies from 0 to 40 Hz. The total spectral variance was aggregated by means of principal-components analysis, which reduced the 40 frequencies to 4 frequency dimensions. These represented the characteristic spectral ranges of the EEG activity: slow activity between 1 and 6 Hz (theta, delta), slow alpha activity between 6 and 9 Hz, fast alpha activity between 9 and

13 Hz, and fast activity greater than 13 Hz, nowadays addressed as *beta* and *gamma* activity.

One finding was that the EEG signal proved equally dependent on both personality differences and situational demands. For example, the fast alpha of 9 to 13 Hz differentiated clearly between more passive situational demands (rest, listening, noise) and more active periods (mental calculation), but this effect was much more pronounced for the introverted participants than for the extraverted ones (see Figure 3). Similarly, very slow alpha activity, which is a sign of deactivation, increased over the course of the experiment much more for extraverts than for introverts. So, the study proved that there is systematic, psychologically relevant variance in the spontaneous EEG signal reflecting situational demands and personality traits. Most interesting is that the effects did not appear as habitual differences between participants but rather as dynamic differences; that is, extraverts and introverts did not differ at rest, but only if they were challenged by an arousing situation. The EEG signal proved to be a function of the interaction of personality traits and situational demands. Similar findings have been reported (e.g., Becker-Carus, 1971; Beyer, Pickenhain, & Schumann, 1976; Dolce & Waldeier, 1974; Gale, Coles, Kline, & Penfold, 1971; Gale, Morris, & Lucas, 1972; Pawlik & Cattell, 1965). It was received as a very important finding that the EEG signal proved as dependent on psychological variables that could not

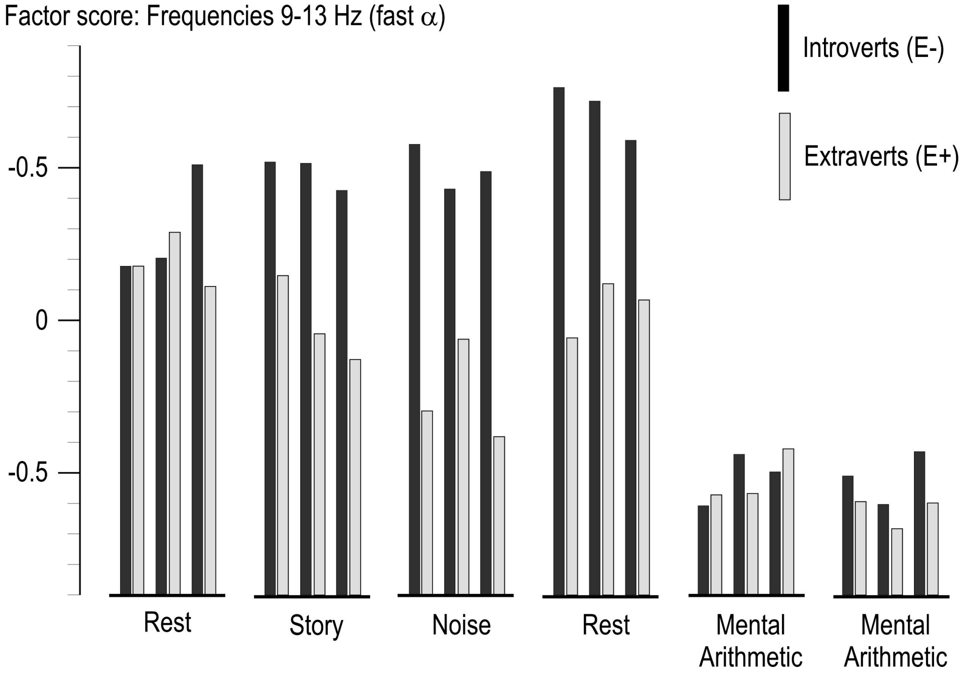

Figure 3. Influence of situational and personality variance on the fast alpha activity. Fast alpha power differs between more passive situations (rest, listening to a story, listening to noise) and more active situations (mental arithmetic), but this difference is more pronounced for introverts than for extraverts. Based on data from Rösler (1975a).

be defined by the physical variables of an experimental situation alone. (For example, the EEG responded differently in two situations in which the very same mental calculation problems had to be solved but in which the participant either had or had not received an additional stress-inducing instruction. Thus, besides the instruction, everything was identical in the two test situations.)

Although these were striking results, the approach has its obvious limitations. First, only a small amount of the total variance of the EEG signal was explained by the frequency bands at all. In the study just described (Rösler, 1975a), only 8% of the signal variance was explained by main effect situations, and only 2% was explained by main effects of personality traits and by the interactions of Personality × Situations (see Rösler, 1975b). More important, however, is the fact that only states of longer duration could be studied (rest, vigilance, mental calculation), not brief epochs of information processing that are closely related to external events and well-defined psychic processes (e.g., access to memory contents, preparation of speech output, etc.). That is, the state definitions in these studies were very coarse; they could be mapped only onto very broad constructs, such as vigilance or arousal, but not onto the more narrowly defined subprocesses as they were postulated by the then-evolving new discipline of cognitive psychology (e.g., Estes, 1975; Neisser, 1967; Posner, 1978).

The Second Step: Averaging, Event-Related Potentials, and Information Processing

It was G. D. Dawson (1947) who introduced a new paradigm that allowed a more specific analysis of the EEG signal and that permitted closer links between psychic events and brain electrical responses. Dawson was the first to find a method to record event-related potentials (ERPs) from the unopened skull. On the basis of Caton's (1875) observations, he thought that systematic ERP changes should also exist in the EEG recorded from the scalp. These, he thought, were hidden in the spontaneous changes, because they had a relatively small amplitude. In a first approach, he simply superimposed stimulus-triggered EEG epochs as time-locked signals onto a storage oscilloscope. The result was striking: Stimulation of the left arm, for example, resulted in systematic, stimulus-locked deflections over the right somatosensory cortex, and stimulation of the right arm resulted in comparable responses over the left somatosensory cortex. This proved that ERPs can indeed be recorded from the unopened skull. The amplitude of these signals was very small compared with the spontaneous—that is, not stimulus- or response-locked—potential changes (5 vs. 50 μV), but by increasing the signal-to-noise ratio they could be reliably detected.

In order to extract the small stimulus-locked signals from the spontaneous "noise," Dawson (1954) constructed an electro-mechanical averaging machine. I will not go into the technical details but only outline the general principle (see Figure 4). The amplitude of the signal was recorded in each trial (e.g., each stimulus repetition) at discrete and equidistant times, and these amplitudes (electrical potentials) were added to capacitors. A fixed number of capacitors (32 or 64) was used for an equivalent number of subsequent points in time. The first trial loaded the subsequent amplitudes on the separate capacitors. In the next trial, the amplitudes of equivalent times (in relation to stimulus onset) were added to the

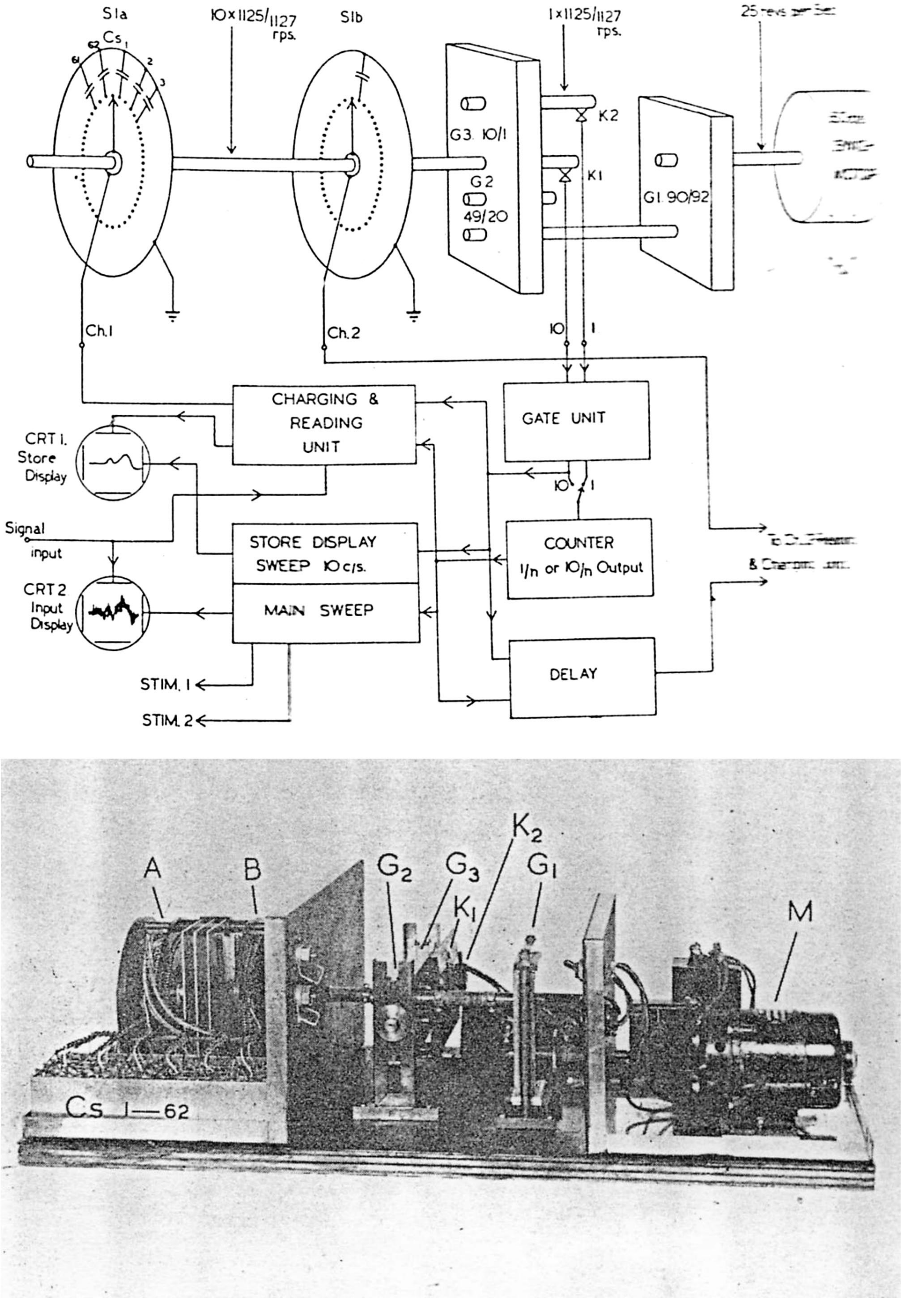

Figure 4. The first signal averager for extracting event-related potentials from the electroencephalogram. From “A Summation Technique for the Detection of Small Evoked Potentials,” by G. D. Dawson, 1954, *Electroencephalography and Clinical Neurophysiology*, *6*, pp. 69 & 75. Copyright 1954 by Elsevier Science. Reprinted with permission.

potentials of the capacitors, and so forth. So, after a series of *n* trials, unsystematic shifts of the signals—that is, those not related to the stimulus—leveled off to zero, whereas those systematically related to the stimulus were kept and became visible. The result could be read out of the capacitors as amplitude values and plotted on paper or could be shown on a storage oscilloscope. As can be seen in Figure 5, random fluctuations are present in each single trial but already in an average of the first five trials the systematic, stimulus-locked amplitude changes can be seen clearly.

This new method was soon adopted by many laboratories. So-called e*voked potentials* were recorded for stimuli of different modalities, and it was observed that the features of these signals, their latency and amplitude—for example, loudness and pitch of auditory stimuli, or brightness and color of visual stimuli—varied as a function of the stimulus features. Dawson's (1954) discovery that ERPs could be extracted from the EEG by improving the signal-to-noise ratio had a great impact on the field, but the great breakthrough did not happen before the technique of signal averaging was transferred onto digital computers. This oc-

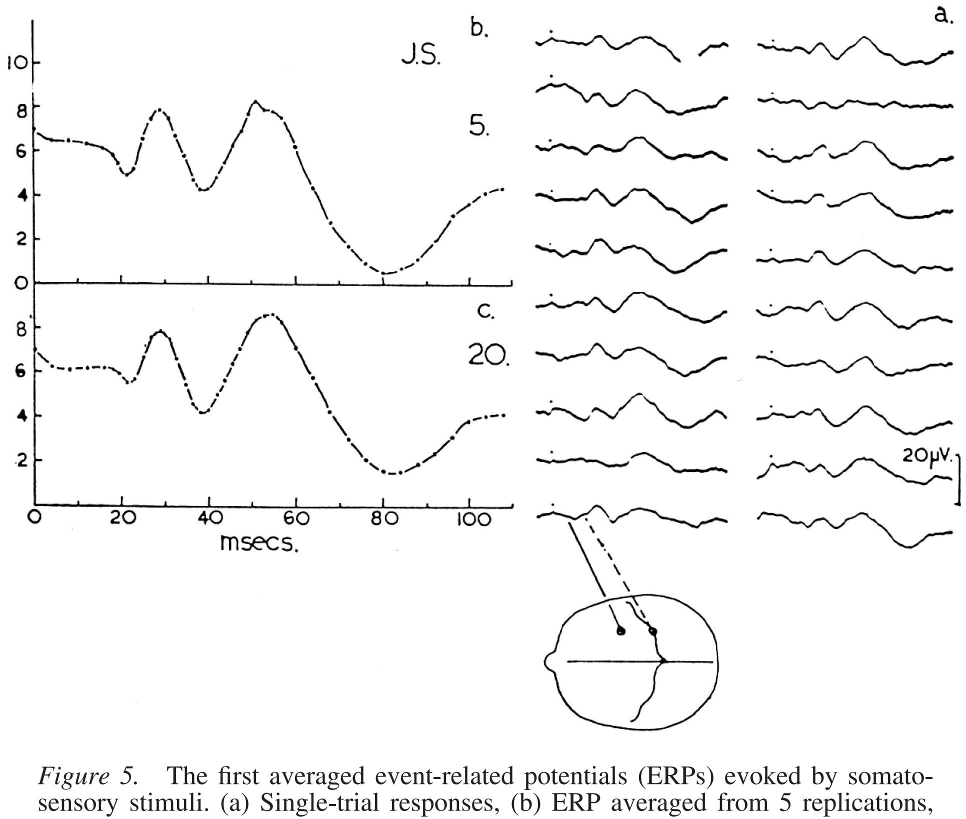

Figure 5. The first averaged event-related potentials (ERPs) evoked by somatosensory stimuli. (a) Single-trial responses, (b) ERP averaged from 5 replications, and (c) ERP averaged from 20 replications. Stimulation was at left arm; recording electrodes were located over right motor-somatosensory cortex. From "A Summation Technique for the Detection of Small Evoked Potentials," by G. D. Dawson, 1954, *Electroencephalography and Clinical Neurophysiology*, *6*, p. 67. Copyright 1954 by Elsevier Science. Reprinted with permission.

curred around 1960, and by the mid-1960s a great number of articles appeared in which evoked potentials had been systematically recorded and in which basic psychophysical and physiophysical relationships were described (e.g., Löwenich & Finkenzeller, 1967; Shipley, Jones, & Fry, 1965). Such physiophysical relationships were exciting because they allowed an objective measurement of sensory processes, and they were soon used for diagnostic purposes by neurologists. At the same time, researchers started to look for higher order psychophysiological relationships, that is, ERP effects that were predictable not from the physical features of the stimuli but rather from the psychological context of the experimental situation. Three such psychophysiological discoveries were made around 1964.

The first genuine psychological ERP effect was discovered by Gray Walter, a British physiologist working in Bristol; the details were published in *Nature* in 1964 (Walter, Cooper, Aldridge, McCallum, & Winter, 1964). Walter had begun his work in Lord Adrian's laboratory around 1940. Together with his colleagues, he observed that a very pronounced negative shift appeared between paired, predictable stimuli. This effect was most pronounced if the participant had control over the situation in that he or she could terminate the second stimulus by a button press. The authors labeled the phenomenon *contingent negative variation* (CNV; see Figure 6). In the publication it was related to the construct of "expectancy," and very soon the CNV was called the *expectancy wave*. It was not completely clear in Walter et al.'s (1964) publication whether the CNV was really related to such an abstract concept as expectancy or rather to the process of movement preparation. Nevertheless, the finding showed that a psychic phenomenon such as expecting a subsequent stimulus or preparing for a forthcoming motor response became manifest in the EEG signal.

As a matter of fact, later research showed that the CNV is not necessarily connected to an overt motor response. Pure expectation of a stimulus is sufficient to evoke such an event-related negativity (Brunia, 1988). However, an intentional initiation of a motor response can also cause a negative potential over the motor projection areas. This was discovered not long after Walter et al.'s (1964) publication by two German researchers (Kornhuber & Deecke, 1965) who showed that a voluntary movement is preceded by a typical ramplike negativity. The phenomenon was labeled *Bereitschaftspotential* ("readiness potential"; see Figure 7). This phenomenon was fascinating, because it proved that the EEG allows one to monitor an intention or the onset of a voluntary motor act long before an overt response becomes detectable (see also Libet, 1981, 1985, and Haggard & Eimer, 1999).

The third remarkable effect was discovered by Sam Sutton and his colleagues while they studied participants in the so-called *modality shift paradigm* (Sutton, Braren, Zubin, & John, 1965). Two types of stimuli—light flashes and acoustic tones—were presented in random succession, some predictable and others not, and the respondents had to predict the next stimulus. It was observed that stimuli that were unexpected (uncertain) evoked a pronounced positivity in the EEG approximately 300 ms after stimulus presentation. This phenomenon was called *P300*, and many studies were conducted to delineate its functional significance (see Figure 8). This proved to be a rather arduous task, because even very complex, objectively defined variables of the experimental situation—as, for

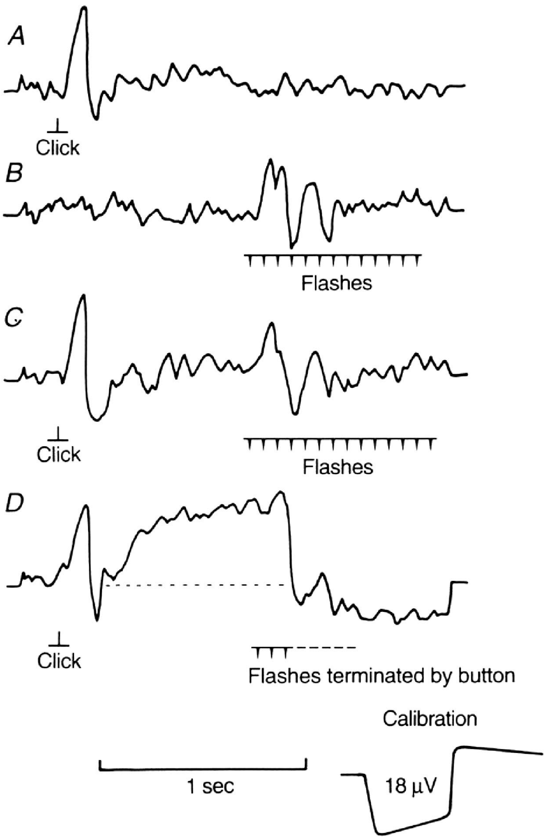

Figure 6. Demonstration of one of the first "cognitive" event-related potentials, the contingent negative variation (CNV). Panel A: response to clicks. Panel B: response to visual flicker stimuli. Panel C: response to clicks followed by flicker. Panel D: clicks followed by flicker terminated by the participant pressing a button as instructed. A CNV follows the click if it predicts the task-relevant flicker associated with an imperative response. Negativity is up in this and Figures 7–10. From "Contingent Negative Variation: An Electrical Sign of Sensorimotor Association and Expectancy in the Human Brain," by W. G. Walter, R. Cooper, V. Aldridge, W. C. McCallum, and A. L. Winter, 1964, *Nature*, *203*, p. 381. Copyright 1964 by the Nature Publishing Group. Reprinted with permission.

example, the a priori probability of a set of stimuli—did not completely covary with the amplitude and latency of the P300. Today we know that at least two psychological constructs are relevant to evoke a P300 component: (a) subjective probability and (b) task relevance of an event. The smaller the subjective probability, and the more task relevant a stimulus is, the larger becomes the amplitude. The latency seems to be related to the difficulty of stimulus discrimination; for example, stimuli that are difficult to extract from a noisy background prolong the latency of the P300 (Donchin & Coles, 1988; Rösler, 1982). As a possible construct it was suggested that "context updating" might capture the process that becomes manifest in the P300, that is, the brain always extrapolates from the

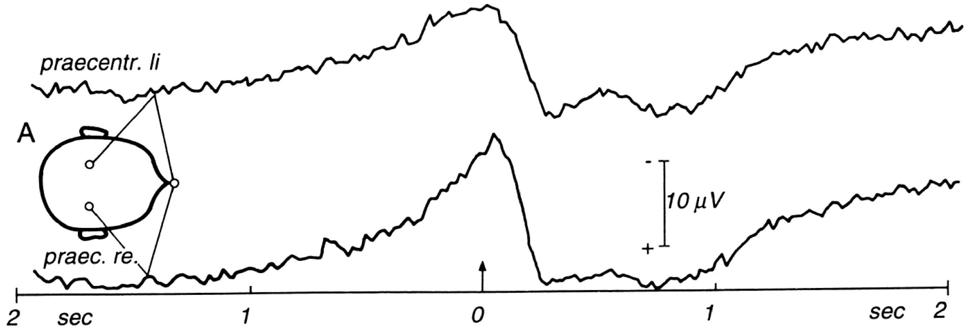

Figure 7. Event-related brain potential changes during preparation and execution of a voluntary movement of the left hand. Movement onset is indicated by an arrow at Time 0. The movement is preceded by a ramplike increasing negativity, the readiness potential, which is larger contralateral to the side of movement. "praecenter. li" and "preac. re" denote the electrode locations over the left and right precentral cortex. sec = seconds. From "Hirnpotentialänderungen bei Willkürbewegungen und passiven Bewegungen des Menschen: Bereitschaftspotentiale und Reafferente Potentiale," by H. H. Kornhuberand and L. Deecke, 1965, *Pflügers Archiv für die gesamte Physiologie*, *284*, p. 7. Copyright 1965 by H. H. Kornhuberand, L. Deecke, and Springer-Verlag. Reprinted with permission.

available evidence the most likely next event. Whenever the system encounters a stimulus that does not fit into the expected and prepared processing schema, a kind of context-updating routine has to be called in to handle the new situation, and this seems to be reflected by the P300 phenomenon. Context updating as just described is a very abstract construct, but it shows that the functional significance of these psychologically relevant ERP components is not easily captured by a straightforward description of the experimental situation (Rösler, 1983).

A few years later, another fascinating effect was described by Steve Hillyard. He was able to objectify the construct of selective attention by means of ERPs (Hillyard, Hink, Schwent, & Picton, 1973). If participants listen to streams of acoustic stimuli that arrive either to the left or right ear with the instruction to detect critical stimuli in one ear and to ignore all other stimuli, then a typical difference between attended and nonattended stimuli can be observed. The attended stimuli always evoke a larger amplitude of two early components with a latency of approximately 100 ms to 200 ms after stimulus onset (N1–P2). The interesting finding was that the amplitude difference appeared even though the stimuli were physically the same in the attended condition and in the unattended condition; that is, the difference in the N1–P2 amplitude had a purely psychological cause—whether the stimuli were attended or not. Moreover, the effect was not restricted to the relevant targets but was present in all ERPs evoked by stimuli of the attended channel. So all stimuli of an attended "channel" seem to be amplified, whereas stimuli of all ignored channels seem to be attenuated.

These four discoveries paved the way for a new, psychophysiological research paradigm (see Figure 9). The normal approach in cognitive psychology can be described as follows: The researcher manipulates the input of the system and

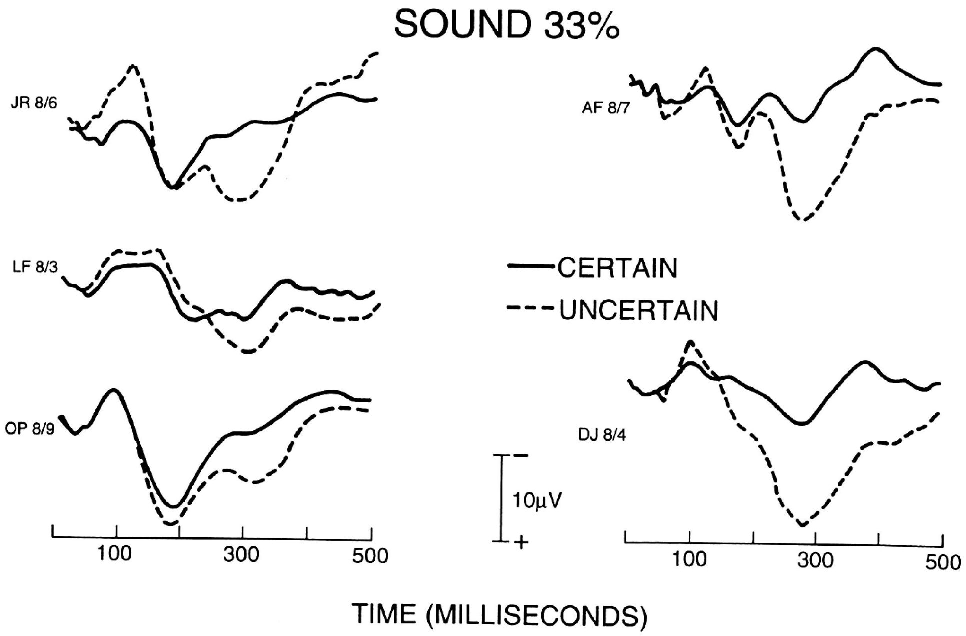

Figure 8. Event-related potentials of 5 participants evoked by certain (predicted) and uncertain (unpredicted) sounds. Uncertain sounds evoke a strong positivity, the P300 component. JR, LF, OP, AF, and DJ are the initials of research participants. From "Evoked Potential Correlates of Stimulus Uncertainty," by S. Sutton, M. Braren, J. Zubin, and E. R. John, 1965, *Science*, *150*, p. 1187. Copyright 1965 by the American Association for the Advancement of Science. Reprinted with permission.

observes its output. Then he or she tries to explain the transfer function of the system by relating the two pieces of observation: input and output. However, with this approach it is not possible to monitor the intervening processes directly. This is different with the ERP and other brain imaging tools. Such phenomena can be observed parallel to information processing proper, and the effects can be related to intervening processes. By means of this, the degrees of freedom for theory building are reduced.

The psychological phenomena that become manifest in ERPs can be of a very high conceptual level. One of these high-level effects was first described by Kutas and Hillyard (1980). Marta Kutas, at that time a postdoctoral research fellow in Steve Hillyard's laboratory, observed that words that do not fit into a previously established semantic context evoke a very pronounced negativity over the central and parietal cortex (e.g., "He spread the warm bread with socks" vs. "It was his first day at work"). The negativity starts about 200 ms after presentation of the nonfitting word, reaches its maximum at around 400 ms, and resolves during the following 300 or 500 ms (see Figure 10). The phenomenon has been labeled the *N400 effect*, and it describes the potential difference between fitting and nonfitting words. One could argue that the effect is a manifestation of the odd stimulus, but as shown by Kutas and Hillyard, this is not the case. Physically deviant stimuli

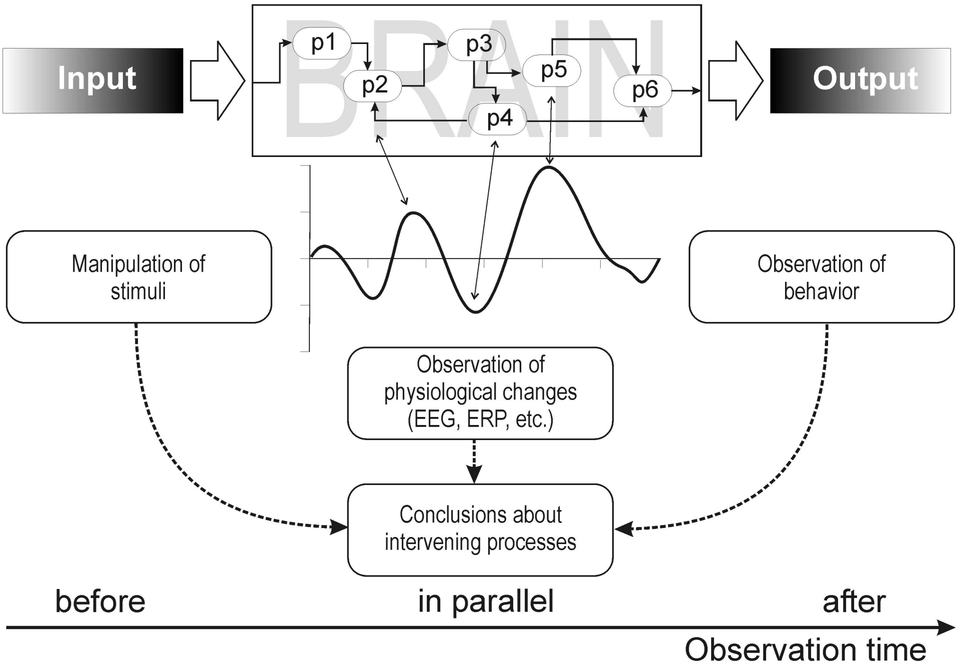

Figure 9. Schematic outline of the psychophysiological research paradigm. Traditional psychology manipulates input, observes output, and draws conclusions about the intervening processes from these two pieces of information. Psychophysiology observes in addition biological changes (event-related potentials, etc.) the timing and amplitude of which can be related to the timing and extensiveness of intervening processes. Based on Rösler (1983) and Rösler and Heil (1998).

evoke not an N400 effect but rather a P300 type of phenomenon. The N400 effect seems to be closely related to semantic integration processes. These do not necessarily have to be triggered by words; a prerequisite is only that the stimuli transmit semantic information. Similar effects can be observed with mental calculation problems having an incorrect solution (Niedeggen & Rösler, 1999), musical tunes that are completed with a nonfitting note (Besson & Macar, 1987), or pictures and word sequences that tell a story and that are completed with a nonfitting picture (Nigam, Hoffman, & Simons, 1992). The effect is also independent from the stimulus modality (auditory, visual) or the language (English, German, spoken language or sign language; Holcomb & Neville, 1990; Neville, 1985; Van Petten, Kutas, Kluender, Mitchiner, & McIsaak, 1991). Significant for eliciting an N400 effect is a meaningful context and a piece of information that cannot be integrated because of semantic restrictions. Such an effect can also be observed with word pairs, and in that case the amplitude of the N400 effect seems to reflect the associative relatedness between prime and target; that is, a word that is less primed by the preceding word evokes a larger N400 effect (e.g., Bentin, McCarthy, & Wood, 1985; Münte, Künkel, & Heinze, 1989).

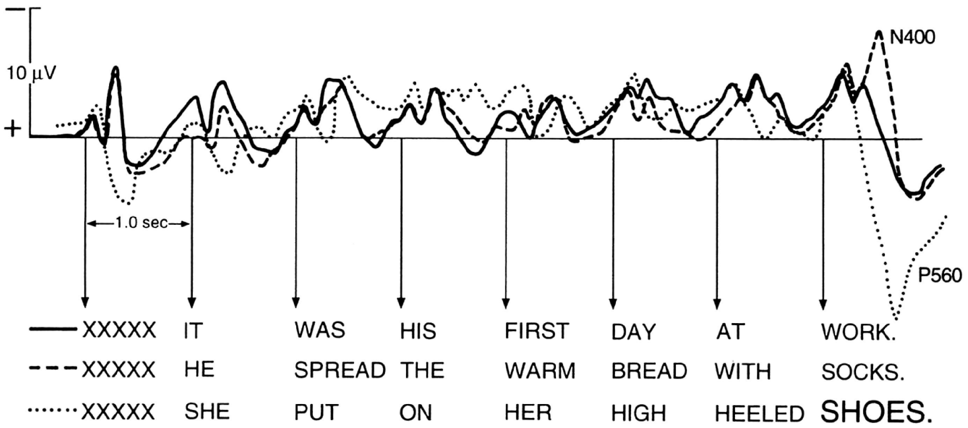

Figure 10. High-level cognitive ERPs. Participants read the sentences word by word. The last word was printed in the same type size as the preceding sentence fragment and made either a meaningful completion (WORK, continuous line) or not (SOCKS, dashed line), or it was a meaningful completion but appeared in a larger font. The semantic deviation evoked an N400 effect, a relative negativity effect, and the physical deviation evoked a P300 effect, a relative positivity effect. sec = seconds. From "Reading Senseless Sentences: Brain Potentials Reflect Semantic Incongruity," by M. Kutas and S. Hillyard, 1980, *Science*, *207*, p. 203. Copyright 1980 by the American Association for the Advancement of Science. Reprinted with permission.

The Present: Topographic Analysis and Event-Related Spectral Analysis

ERP components originally were defined by polarity and latency only, but today, with better technical equipment, another dimension is added. The EEG can now be recorded easily from many channels simultaneously, and this allows researchers to study topographic changes that are related to experimental manipulations. Moreover, with mathematical tools the location of generators can be estimated from the surface recordings, provided the electrodes are placed densely enough and the estimate is further constrained, for example, by the individual cortex anatomy measured with structural functional magnetic resonance imaging (fMRI; Haan, Streb, Bien, & Rösler, 2000; for further technical details see, e.g., Berg & Scherg, 1994; Buchner et al., 1997; Fender, 1987; Junghöfer, Elbert, Leiderer, Berg, & Rockstroh, 1997).

With the following example, I show that topographic changes of ERPs also have relevance for understanding and disentangling psychological processes. Streb, Rösler, and Hennighausen (2004) studied ERPs in participants who had to resolve anaphora, that is, when they had to relate a currently processed word to the preceding context. Language provides different types of anaphora, for example, the simple repetition of a name is such a connecting device ("Paul and Jerry go to the cinema. Paul is very excited"), another is an ellipsis ("Tom eats bananas and Shirley oranges"—*eats*—has to be inserted mentally as a verb between "Shirley" and "oranges" to make a meaningful message out of the utterance). With such material, Streb et al. observed two effects. When an ellipsis has to be resolved, a left anterior negativity (LAN) appears in the ERP. This phenomenon is not present when so-called *model interpretative* anaphora are resolved (e.g., “Paul gives a nice chain to Anna, and John buys Anna a ring”). Here, the listener/reader has to understand that Anna is the same person; that is, he or she has to integrate the Anna of the two sentences into one model that represents the meaning of both propositions). With such a model-interpretative anaphora no LAN but rather an N400 type of effect can be observed, which is not present with the ellipses. These two effects have a clearly distinct topography: The ellipses-related negativity is more anterior and left sided, its generator could be located in Broca’s area, whereas the model interpretative negativity is more posterior and right sided. It has the typical topography of an N400 effect. Thus, the distinct topography of the ERP phenomena that accompany the two distinct anaphoric devices suggest that the system uses functionally distinct processes to connect ongoing and preceding discourse (Garrod & Sanford, 1994). The first phenomenon, the LAN, seems to be related to syntax analysis, whereas the second, the N400 type negativity, seems to be a manifestation of semantic integration processes.

Finally, modern experimental EEG research has also rediscovered spectral analysis. The original disadvantage that the frequency spectrum could be determined only for a longer, stationary epoch, and therefore be related only to longer lasting and global constructs, such as arousal, has now been overcome by an extension of the approach. Now, the spectrum is determined for short epochs (e.g., 250 ms) with a moving-windows technique. This allows one to monitor event-related and continuous changes of frequencies. Moreover, these analyses can also be applied to a set of recordings from many electrodes such that topographic changes of dominant frequencies and coherence patterns between different scalp locations can be studied (e.g., Jürgens, Rösler, Hennighausen, & Heil, 1995; Klimesch et al., 1996; Tallon-Baudry & Bertrand, 1999). The psychological concepts that are related to these phenomena are, among others, local and global binding mechanisms that integrate the distributed elementary processes to coherent percepts and memory entities (see, e.g., Eckhorn et al., 1988; Engel & Singer, 2001; Singer, 1990; von Stein, Chiang, & König, 2000).

Conclusions

The EEG has become a very successful tool to study human information processing. The reasons for this success are numerous. First, the EEG can be measured during behaviorally mute epochs—between stimulation and before a response becomes visible as behavior. Thus, measures derived from the EEG, such as ERPs or event-related spectral changes, enlarge the domain of dependent variables, and these can be directly related to intervening processes (see Figure 9). Second, research has shown that the EEG phenomena bear straightforward relationships to genuinely psychological constructs such as expectation, subjective probability, selective attention, semantic integration, and so forth. The variance of ERP phenomena can be explained only if the psychological context of an experiment is taken into account, that is, if instructions, task set, personality traits, subjective experiences, and objective indices of behavior (response speed, errors, etc.) are considered in addition to the physical setup. This feature makes them very attractive. Third, the temporal resolution of ERPs and event-related frequency changes are in the same order of magnitude as the cognitive processes that are postulated on the basis of purely behavioral experiments. These timing parameters vary between a minimum of 30 ms and a maximum of a few seconds. For example, first selective attention effects seem to take place within the sensory projection areas and become manifest not later than 30 to 50 ms after stimulus onset; lexical access is assumed to be accomplished within 150 to 200 ms; an inhibition of irrelevant representations in conflicting situations, as in the Stroop paradigm, need little more than 50 to 100 ms; and difficult mental transformation processes, as in a mental rotation paradigm, need a maximum of 1 or 2 s. These are exactly the timing magnitudes that are measured as latencies of subsequent ERP components and event-related frequency changes. Thus, EEG measures seem to be direct manifestations of covert processes. Fourth, the method is noninvasive; that is, it can be used by psychologists without the assistance of a physician. Moreover, it can be used repeatedly without doing any harm, and this permits long-lasting and repeated measurements with the same sample of subjects. Fifth, the method is comparably inexpensive. Nowadays, a multichannel EEG laboratory costs not more than 30,000 to 50,000 Euro. This is far less than what has to be invested for any other brain imaging device (positron emission tomography, fMRI).

All in all, the EEG, and in particular event-related measures, opened new windows for studying human information processing. When other modern brain imaging tools (positron emission tomography and fMRI) became available around 1990, one could often hear that the EEG will soon be history, because these other methods will do a much better job. They open a real window into the mind because they permit one to reconstruct a three-dimensional picture of brain activity. It is true that the EEG mostly reflects activity from the surface of the brain and that these activity measures have a limited spatial resolution. In this respect, the fMRI is much better, in particular if high magnetic fields are used (3 Tesla scanner). However, spatial resolution is only one aspect. The great advantage of the EEG is its temporal resolution and its direct relation to neural activity. The EEG reflects the summed electrical activity of neural cell assemblies—most likely postsynaptic potentials (Creutzfeldt, 1995; Creutzfeldt & Houchin, 1974; Elbert, 1993; Mitzdorf, 1991; Speckmann & Caspers, 1979) and, therefore, it provides a very immediate measure of neural activity. The fMRI, on the other hand, reflects changes of blood supply within circumscribed volumes of brain tissue with a latency of about 2 s. This is an indirect measure of neural activity only, and the latency is longer than the time needed by most of the cognitive processes that intervene between input and output and that activate the neural cell assemblies. Thus, many effects that can be seen with the EEG cannot be seen on principle with the more indirect measure of an event-related fMRI.

EEG research has always been closely dependent on the available technological developments. Berger's achievements were possible only because of the availability of radio tubes developed for electronic amplifiers. Dawson's (1954) idea to improve the signal-to-noise ratio by means of averaging was triggered by the rapid improvements of telecommunication techniques that faced the very same problem: How can a small electromagnetic signal be detected in a noisy background? The next great step forward in experimental EEG research became possible because of the development of digital computers, which allowed researchers to apply advanced methods of signal analysis to the EEG time series that comprised several thousand measures if only one channel was sampled with a digitization rate of 200 Hz. A Fourier transformation of such a signal without a digital computer could hardly have been managed. The currently available technology always restricted or even determined the scope of the research questions. The first mainframe computers allowed an analysis of only one or two EEG channels—the limitation was given by the speed of the central processing unit and by the size of the core memory. With the development of lab computers (e.g., the PDP 8), workstations (e.g., the DEC alpha), and now the most powerful PCs (e.g., the Pentium 4 with dual processors of 2.4 GHz and a core memory of several megabytes), the analysis has become more and more extensive and sophisticated. Today, it is no longer a problem to record and process signals simultaneously from 256 channels with a digitization rate of 1,024 Hz. This gigantic set of data—1 minute of recording time generates 15,728,640 data points—can be analyzed with advanced signal extraction methods (e.g., wavelet analysis and other digital filter algorithms) as well as with continuous spectral and coherence analysis methods in reasonable times.

New technological developments always open new research windows, but the currently available techniques also set the boundaries for what can be discovered, and they also shape the research questions and the theoretical concepts that are used to explain the findings. Within these limitations, the EEG has had a substantial impact on the development of experimental psychology. It changed the paradigm in that dependent variables have become available that can be recorded during epochs that are psychologically uninformative. The EEG can be recorded while a person is thinking without showing any overt behavior, and in this situation the EEG provides measures that are systematically related to the prevailing mental activities. This technological progress coincided with the conceptual developments in cognitive psychology. Cognitive psychology abandoned the paradigm of classic behaviorism in that researchers did not restrict their studies to input–output relations only but tried to fill the "black box" with specified intervening processes. The combination of both scientific developments—measurements during behaviorally mute epochs and formulation of intervening processes for the behaviorally mute epochs—increased substantially researchers' understanding of how the mind works. This is particularly true for the research areas of selective attention (Mangun & Hillyard, 1995; Näätänen, 1992), memory (Rugg, 1995), and language (Brown & Hagoort, 1999; Hagoort, Brown, & Osterhout, 1999). However, there is another aspect that added to researchers' knowledge and that changed the concepts of experimental psychology. Psychological theories can be formulated without any relationships toward the biological basis of the mind. At the beginning, this was indeed the explicit program of cognitive psychology. This approach did not care about physiological concepts and the constraints set by biology. However, by referring to biosignals, and in particular by using direct measures of brain activity, the conceptual approach changed. Latencies and amplitudes of ERP components were seen at first as any other dependent variable—for example, response time and error rate (Donchin & Israel, 1980)—but it was soon acknowledged that they are always related to physiology, too (Goff, Allison, & Vaughan, 1978). Thus, measures derived from the EEG always have a double theoretical connection: On one side, they are incorporated into psychological theories; they can be interpreted as manifestations of hypothetical constructs and intervening processes, and on the other side, they are directly related to the biological substrate; they result from activity changes in circumscribed neural networks and therefore can provide the basis for formulating genuine psychophysiological relationships.

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