Chapter One

The Central Nervous System

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INTRODUCTION

Psychophysiology shares concepts and methods with both psychology and physiology. With psychology, it shares the conceptual objective of understanding the psychological processes responsible for human behavior and the methodological tools of behavioral experimentation. With physiology, it shares a conceptual emphasis on biological substrates of behavior and a methodological emphasis on dependent variables that reflect activity of parts or components of the organism under study. In our view, what distinguishes the research of investigators who consider themselves "psychophysiologists" from other approaches to the combined study of physiological and behavioral variables is an emphasis on *noninvasive measurement of physiological variables in conscious, behaving human subjects*.

Our purpose in this chapter is to assess the value and limitations of noninvasive measurement of human central nervous system (CNS) activity. We have restricted the broad scope of that question in two ways. First, because of our own experience and research interests, we concentrate on event-related potentials (ERPs) recorded in association with specific stimulus and response events. We do not explicitly address research using the electroencephalogram (EEG) or other noninvasive techniques, such as magnetic recordings of human brain activity. However, many of the issues to be considered apply to all such noninvasive techniques. Second, although applied research using ERPs has resulted in their widespread use as clinical tests in neurology and related fields (e.g., Chiappa & Ropper, 1982; Halliday, 1978; Starr, 1978), our discussion emphasizes the use of ERPs to investigate psychological processes and their biological substrates.

Our assessment of surface ERPs as noninvasive measures of CNS activity begins with a review of how electrical events in the CNS are generated. We then discuss examples of surface ERPs generated by various structures of the somatosensory system. Next we consider the implications of the review and examples for ERP studies, and we conclude with a somewhat irreverent but (we hope) instructive comparison of classical and modern "bumpology."

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THE NERVE OF LORENTE DE NÓ: SOME FUNDAMENTALS OF NEURONAL ELECTROGENESIS

Ionic current flow across the cell membranes of active neurons gives rise to electrical potential differences between different locations in the extracellular space, which can be recorded between a pair of electrodes located in, or in electrically conductive contact with, that space. Because the brain and its coverings (the meninges, skull, muscle, and scalp) are electrically conductive media, surface ERPs are subject to the same laws and principles of electrical field theory that govern the recording of electrical potentials in any volume conductor (e.g., Freeman, 1975).

Two types of transmembrane current flow (and hence extracellular potentials) are intimately related to information transmission and processing within and between neurons. The first is associated with the all-or-none spike or action potential, which reflects transmission along an axon from the cell body to axon terminals. The second is associated with graded postsynaptic potentials (PSPs), which reflect information transmission from one neuron to another. The latter can be either excitatory (EPSPs) or inhibitory (IPSPs).

First, let us consider the generation of action potentials. During the 1930s and 1940s, many neurophysiologists studied compound action potentials—that is, the summation of many individual action potentials of single nerve fibers—generated by electrical stimulation of peripheral nerves. A classic and still instructive experiment was performed by Lorente de Nó (1947b), which exemplifies many of the fundamental characteristics of extracellularly recorded neuronal electrical activity. His recordings are illustrated in Figures 1-1A and 1-1B, and summarized schematically in Figures 1-1C and 1-1D. When the neuron is at rest (Figure 1-1C, section 1), there is no current flow across the cell membrane, and the extracellular potential is consequently zero. As the region of membrane depolarization associated with the action potential approaches the recording electrode, a positive potential is recorded (Figure 1-1C, section 2). This is seen, for example, in Figure 1-1B at time 1 after the stimulus; at 0 mm the nerve volley has just exited the oil pool and has depolarized the nerve, while 7 mm down the nerve a positive potential is recorded. A negative potential is recorded when the depolarization is adjacent to the recording electrode (Figure 1-1C, section 3). As the action potential passes the electrode (Figure 1-1C, section 4) the potential again becomes positive (e.g., in Figure 1-1B, location 0,0 at time 3), followed by a return to zero potential. Thus, as shown in Figure 1-1B and section 4 of Figure 1-1C, the entire waveform is triphasic: positive, reflecting *outward* current flow toward the approaching region of depolarization; negative, reflecting *inward* current flow in the region of depolarization; and positive again, reflecting a return

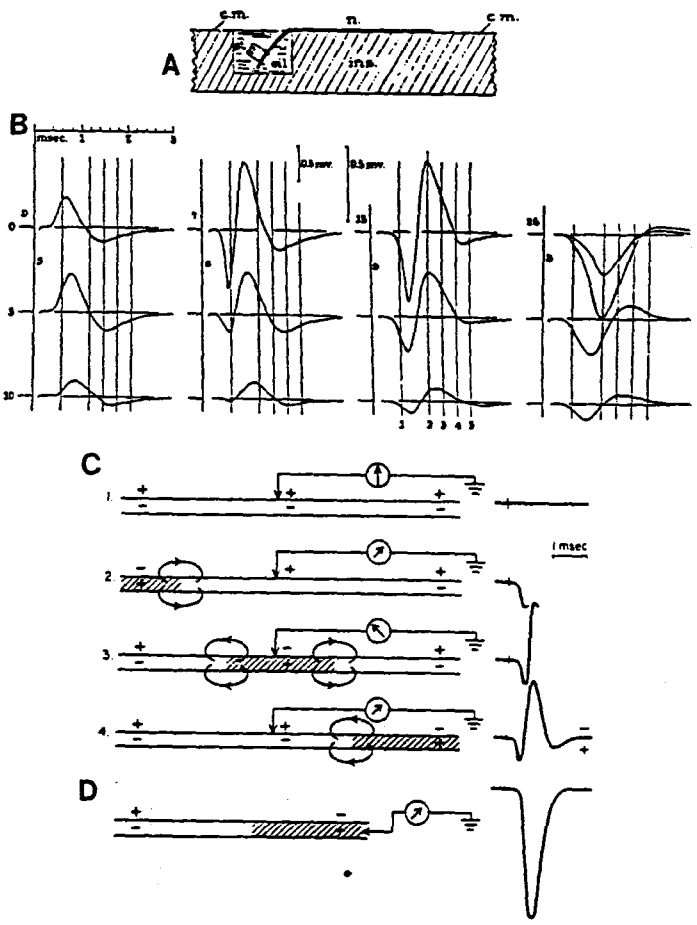

Figure 1-1. Potentials generated by a bullfrog sciatic nerve segment. A. The nerve (n) is laid on insulating material (ins.) covered by a conducting medium (c.m.; a sheet of blotting paper soaked with Ringer's solution). One of the ends of the nerve was submerged in an oil pool in contact with the stimulating electrodes. B. Field potentials produced as the nerve impulses travel from one end of the nerve to the other, recorded from 12 locations. Each column shows the potentials recorded from electrodes located at the indicated distance in millimeters from the point where the nerve exits the oil pool. Each row shows the potentials recorded at a given distance laterally from the nerve. For example, the middle potential in the third column was recorded at a point 15 mm along the nerve and 3 mm lateral to it, which is called location 15,3. The voltage calibration at left is for the top row; the higher gain at right is for the bottom two rows. The reference electrode is on the edge of the blotting paper; negative at the active electrode is upward. The vertical lines note particular times after the stimulus, which in this and following figures is delivered at beginning of trace unless noted otherwise. (Adapted from Lorente de Nó, 1947b.) C, D. Schematic illustration of potentials associated with an action potential traveling along an axon (or compound action potential traveling along a nerve). C. (1) The axon is at rest; there is no current flow, and therefore no potential field. Successive time intervals as the region of membrane depolarization approaches (2), reaches (3), and passes (4) the recording electrode. The complete triphasic positive–negative–positive potential is shown in (4). D. Recording

to *outward* current flow as the depolarization passes. Finally, Figure 1-1B (fourth column) and Figure 1-1D show that an electrode placed at or beyond the end of the nerve records primarily a positive potential. In this case, the region of depolarization approaches but does not reach the electrode. This is an important phenomenon, for it implies that an electrode located beyond the termination of a fiber tract will record primarily a positive potential as a synchronous nerve volley traverses the tract.

Several important generalizations about neuronally generated potential fields are illustrated by Lorente de Nó's recording:

1. Net inward current flow across the cell membrane (often called a current "sink") is associated with a *negative* potential in adjacent regions of the extracellular space.
2. Net outward current flow (often called a current "source") is associated with a *positive* potential in adjacent regions of the extracellular space.
3. Current flow into the active region of the cell is balanced by an equal current flow out of passive regions of the cell.
4. The density of current flow is large in the immediate vicinity of the depolarized region, but decreases rapidly with distance. Since the potential at any point is proportional to the current flow, the amplitude of the potential decreases rapidly as the electrode is moved away from the nerve. For example, at location 15,10, the negativity is only 10% of its amplitude as measured at 15,0. However, the lines of current—and therefore of voltage—extend indefinitely away from the nerve, and under good recording conditions these potentials could be recorded at large distances from the nerve (e.g., 1 m away if the nerve were placed on a large piece of blotting paper or in a bathtub filled with saline).
5. According to Helmholtz's principle of superposition, potentials associated with transmembrane currents of different neurons summate at all locations in the extracellular space. Therefore, potentials of similar latency and morphology from synchronously active cells will tend to summate, producing large-amplitude potentials that can be recorded at considerable distance from their sites or origin. However, the principle of superposition dictates that potentials of opposite polarities also summate, but in this case they tend to cancel rather than reinforce each other. Thus, the instantaneous potential difference between any two locations is the algebraic sum of the potentials due to all transmembrane currents existing at the instant at which the potential difference is measured.
6. Even in a "simple" recording situation like that depicted in Figure 1-1, ERP morphology and latency are complex functions of electrode and source locations, as well as other factors. In the first column of Figure 1-1B, note that the negative peak increases in latency at locations farther from the nerve. Without any knowledge of the location of the source, one might infer that the depolarization was moving from location 0,0 to 0,10. In this case, we know that the region of depolarization is in fact moving perpendicular to this line. Location 0,0 records primarily the potential generated in the segment of nerve immediately adjacent to it; electrode 0,10, on the other hand, is almost as near the first third of the nerve as it is to point 0,0, and therefore records a space-weighted (and hence time-weighted) average of the negativity along that segment of the nerve. Conversely, at the other end of the nerve (the fourth column of Figure 1-1B), electrode 26,10 sees the approaching source positivity from the last third or so of the nerve; thus the peak latency of the positivity is earlier than at location 26,0.
7. The specific potential recorded under a given set of conditions (or, indeed, whether any net potential is recorded) depends both upon the location of the recording electrodes and the location of the active tissue at any instant in time. In Figure 1-1, for example, the active electrode is near the nerve, and the reference electrode is distant. However, if both electrodes were near the nerve, a more complex waveform would be observed, its exact form depending upon the interelectrode distance.

Thus far we have only considered potentials generated by peripheral nerves, which are structurally simple. However, for neurons in the CNS, the situation is more complex. Individual neurons may be structurally complex, with dendrites and axons of various size, shape, and number proceeding in various directions from the cell body. In addition, the structural relationships between neurons may also be complex. Finally, still further complexity is introduced by the pattern of synaptic contacts between cells. Anatomical studies suggest that afferent input to a group of neurons from a particular source usually makes synaptic contact on the dendrites, or on the cell bodies, but usually not on both to an equal extent. Because of superposition, both the spatial orientation of nerve cells and cell groups and the locus and temporal pattern of synaptic activation of those cells are important determinants of the extracellular potentials that can be recorded in any given case, particularly at large distances from the active cells.

Lorente de Nó (1947) investigated the effects of cell orientation in a series of elegant theoretical and

from the end of the nerve yields only a positivity. (From "Generation of Brain Evoked Potentials" by J. Schlag. In R. F. Thompson and M. M. Patterson [Eds.], *Bioelectric Recording Techniques: Part A. Cellular Processes and Brain Potentials*. New York: Academic Press, 1973. Reprinted by permission.)

experimental studies. First consider a simple case in which cell bodies and their dendrites and axons are aligned in parallel (Figure 1-2, left); examples of such neurons are the pyramidal cells of cortex and hippocampus. As in nerve fibers, most of the extracellular current flow is along the long axis of the neuron. Depolarization of the cell bodies by synaptic excitatory action produces inward current flow and a local negative EPSP, while the large vertically directed dendrites serve as the primary current sources, and hence in their vicinity a positive EPSP is recorded. If the EPSPs are large enough, an action potential will be produced, and the entire waveform will consist of the rapid action potential superimposed on the slower EPSP. When the cell bodies are depolarized at about the same time, as by a synchronous afferent volley, their individual potential fields have the same orientation and therefore summate to produce a large potential. Lorente de Nó called the potential field produced by this arrangement of neurons an "open field." Such potential fields can be recorded at considerable distances from their source.

This distribution of potential approximates that created by a theoretical source called a "dipole," which consists of two electric charges of opposite polarity between which current flows. An open field may be thought of as the summation of the elementary dipole sources produced by each neuron. The degree to which the potential field of this "equivalent dipole" resembles that of a theoretical point dipole depends on the areal extent of the neurons and the degree to which they lie in a plane (as in Figure 1-2, left) or have a more complex shape (e.g., if they extend from the crown into the bank of a gyrus).

In many subcortical nuclei, the arrangement of neurons is less regular. Imagine cells arranged in a sphere as shown in Figure 1-2, center, with their dendrites extending radially outward from an inner core of cell bodies. Depolarization of the cell bodies produces extracellular current that radiates inward from the dendrites, leading to a negative potential throughout the structure with a maximum near the center and a zero potential line near the outer border. Outside the structure, there is no current flow and hence no potential. This "closed field," as Lorente de Nó (1947a) called it, is a neurophysiological black hole, invisible from the outside.

Lorente de Nó (1947a) also considered types of potential fields intermediate between open and closed fields. If a structure contains a mixture of cells whose processes have both parallel and radial orientations, an "open-closed" field is produced (Figure 1-2, right). Llinás and Nicholson (1974) suggest that this may be a common arrangement in nuclei, because an otherwise closed field is punctured by parallel axons entering and leaving the nucleus. It can be imagined that an actual potential field could fall anywhere along the continuum of open and closed fields, but these

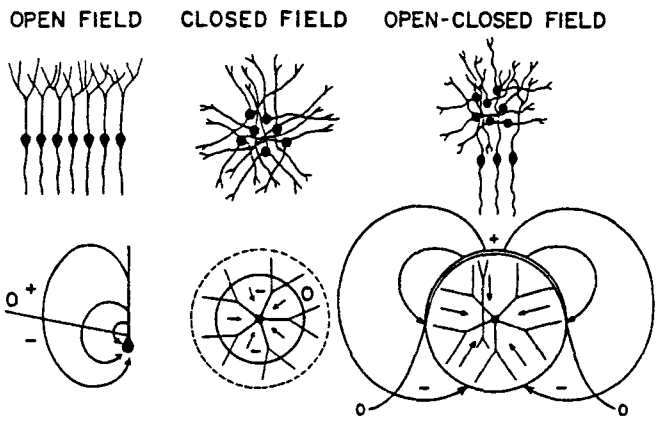

Figure 1-2. Predicted current flow and potential field produced by synchronous depolarization of the cell bodies of a row of neurons with parallel orientation (open field), with cell bodies clustered in the center and with dendrites spreading radially (closed field), and with a combination of radial and parallel elements (open–closed field). (Adapted from Lorente de Nó, 1947a.)

examples will suffice to aid in thinking about potential fields and in developing working hypotheses as to the location and orientation of the neural elements that might generate an observed potential field. For examples of potential fields generated by populations of model neurons that approximate those of certain structures in the mammalian CNS, see Klee and Rall (1977).

FROM THEORY TO PRACTICE: POTENTIALS GENERATED IN THE SOMATOSENSORY SYSTEM BY STIMULATION OF THE MEDIAN NERVE

To illustrate how the principles of electrogenesis reviewed above apply to the interpretation of ERPs recorded from the human body surface, we review the surface ERPs generated in various parts of the somatosensory system. We assume that the median nerve has been electrically stimulated at the wrist (unless noted otherwise), and we follow the resulting afferent volley as it passes up the nerve, enters the spinal cord, and proceeds up the neuraxis. The somatosensory system has been chosen for illustrative purposes because its peripheral portion is accessible to recording, because the neuroanatomy and neurophysiology of the central portion considered here are known in some detail, and because the relationship between surface ERPs and activity of specific anatomical structures has been extensively studied.

Unfortunately, peripheral nerves in a human are not conveniently laid out on a piece of blotting paper, as in Lorente de Nó's demonstration, but are sur-

rounded by muscles and encased in cylinders such as arms and legs. Do compound action potentials produce detectable potentials at the surface of the human body? This question was first answered by Dawson and Scott in 1949; one of their recordings is shown in Figure 1-3 (lower trace). The amplitude of the potential is smaller than those seen in Figure 1-1 because the recording electrodes are farther from the nerve than were Lorente de Nó's electrodes, but otherwise the similarity is striking. Similar recordings can be obtained from an electrode placed on the collarbone overlying the brachial plexus (Figure 1-3, upper trace), where the median and other nerves divide and regroup before entering the spinal cord. The latency of the volley is longer when recorded at the shoulder, the difference corresponding to a nerve conduction velocity of about 60 m/sec.

That a peripheral nerve compound action potential can be recorded from the skin is not a startling result,

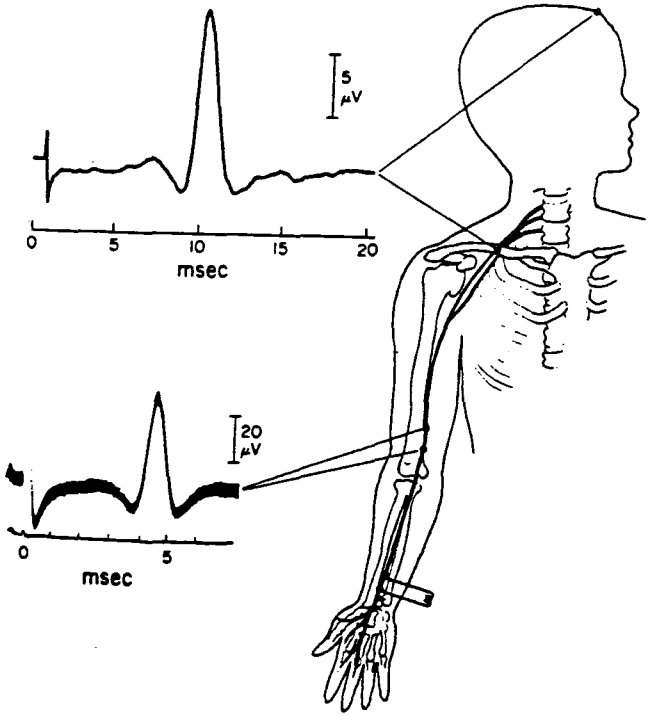

Figure 1-3. Recording of peripheral nerve compound action potentials in humans. Lower tracing: Median nerve volley recorded from the skin just above the elbow. Fifty individual oscilloscope traces were superimposed; negative at distal electrode upward. (From "The Recording of Nerve Action Potentials through Skin in Man" by G. D. Dawson and J. W. Scott. *Journal of Neurology, Neurosurgery and Psychiatry*, 1949, 12, 259–267. Reprinted by permission.) Upper tracing: Median nerve volley recorded from the skin midway along the clavicle overlying the brachial plexus; negative at clavicle electrode upward. Summation of 512 responses.

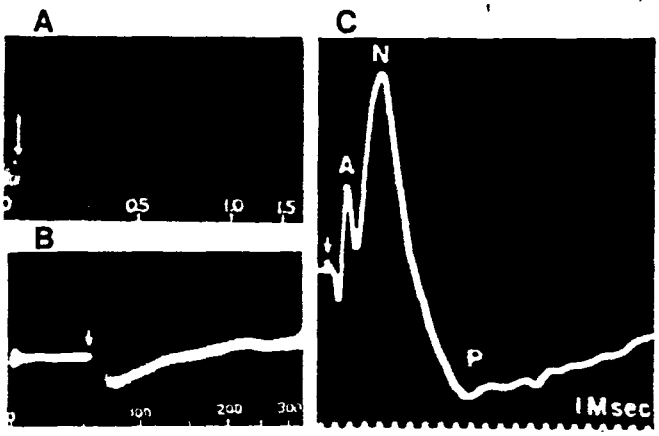

Figure 1-4. Spinal cord recordings. A. Recording of the spike potential evoked by stimulation of a dorsal root in cat. The potential is triphasic positive–negative–positive. B. Similar recording but at a slower speed to show the N and P waves (the N wave is hardly visible). Time is in milliseconds; negative is upward. (From "Potentials Produced in the Spinal Cord by Stimulation of Dorsal Roots" by H. S. Gasser and H. T. Graham. *American Journal of Physiology*, 1933, 103, 303–320. Reprinted by permission.) (C) Potentials recorded from surface of spinal cord in dog to stimulation of a dorsal root. In this recording, the final positivity of the spike potential is obscured by the early portion of the N wave. Stimuli delivered at arrows. (From "Differential Vulnerability of Spinal Cord Structures to Anoxia" by S. Gelfan and I. M. Tarlov. *Journal of Neurophysiology*, 1955, 18, 170–188. Reprinted by permission.)

but for our purposes it allows the important conclusion that surface potentials can be recorded that, in some cases at least, are reasonably faithful reflections of potentials that can be recorded in much closer proximity to their sources within the body. We next follow this nerve volley as it travels through the dorsal roots and enters the spinal cord. In 1933, Gasser and Graham published a remarkable paper. They had set out to study the neural basis of spinal reflexes by recording potentials generated in the spinal cord following stimulation of a dorsal root. For this purpose, they constructed one of the first cathode ray oscilloscopes used for neurophysiological purposes. The tracings they obtained with this instrument were faint and poorly focused (Figures 1-4A, 1-4B); nevertheless, they were able to make a number of important observations when they recorded from the dorsal surface of the cord:

1. They recorded a triphasic positive–negative–positive spike potential, which began about .5 msec after the stimulus and lasted about 1 msec (Figure 1-4A). The spike was immediately followed by slower negative and positive potentials (Figure 1-4B). Figure 1-4C shows a clearer example of these potentials. Gasser

and Graham (1933) referred to the fast and slow portions of the response as the "spike" and "intermediary" potentials. Following Gelfan and Tarlov (1955), we refer to the spike as the "intramedullary primary afferent spike" (A), and the slower potentials as the "N wave" and "P wave."

2. The duration of the A spike was similar to that of a peripheral nerve compound action potential, whereas the N wave has a longer duration.

3. The A spike was resistant to the effects of asphyxia, whereas the N wave was much more sensitive and often disappeared at a time when the spike was unaffected.

4. A conditioning stimulus applied a few milliseconds earlier to the same or a nearby dorsal root had little or no effect on the A spike, but caused a large reduction in the size of the N wave.

5. The N wave was present in deeply anesthetized preparations in which reflex excitation of motoneurons was not possible. In less deeply anesthetized animals, potentials generated by motoneurons in response to dorsal root stimulation occurred later than the N wave.

Gasser and Graham (1933) had little difficulty in concluding that the A spike reflected the afferent volley as it approached and passed the recording electrode. The N wave presented more of a problem, but after reviewing the evidence summarized above, they concluded, "We have presented strong evidence that the prolonged waves in the cord are produced beyond the primary neurone. Motor cell activity alone does not produce them. . . . The burden, therefore, seems to fall on the internuncial neurones" (p. 316).

To determine whether Gasser and Graham were correct, we need several kinds of information. We first need to know the location of the "internuncial neurons," or "interneurons" in current terminology. Wall (1960) recorded from single cells in the dorsal horn of the lumbar cord while touching the animal's hindlimb. He concluded that most of the responsive cells were located in a horizontal band corresponding to laminae IV and V of Rexed (1952) (Figure 1-5A). In this region of the cord, collateral branches of the afferent fibers enter the dorsal horn from the medial side and make numerous synaptic contacts with dendrites of the interneurons (Figure 1-5B). These neurons are aligned in parallel with their dendrites pointing toward the dorsal surface of the cord, their cell bodies situated in laminae IV–V, and their axons proceeding ventrally. Thus we would expect their activation to generate something approximating an open field. However, we cannot directly apply the model of Figure 1-2 (left), which assumes that the *cell bodies* are depolarized, because in the dorsal horn the *dendrites* are depolarized. In this case we would expect to record a negativity in the region of the dendrites and—since the source current necessarily has to come from more

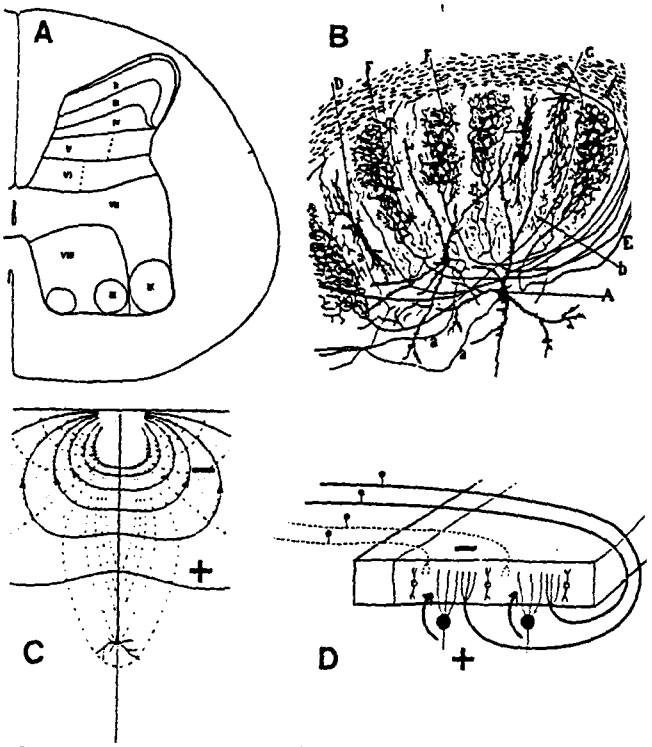

Figure 1-5. Anatomy and electrogenesis of the dorsal horn of the spinal cord. A. The spinal cord is characterized by a number of regions consisting of neurons of particular size, shape, and connectivity. A widely used subdivision is that of Rexed (1952); the example shown is the fifth cervical segment of the cat. B. Collaterals of primary afferent fibers (E) enter the dorsal horn and end in bushy arborizations (F) which make dense synaptic contacts with dendrites of laminae IV–V cells (A) whose axons (a) pass ventrally. (From *Sensory Mechanisms of the Spinal Cord* by W. D. Willis and R. E. Coggeshall. New York: Plenum Press, 1978. [Adapted by Willis and Coggeshall from Ramón y Cajal, 1909.] Reprinted by permission.) C. Theoretical extracellular potential field generated by depolarization of the distal end of a large dendrite of a neuron. Solid lines indicate current flow; broken lines are isopotential lines. For clarity, the most intense parts of the field are omitted. Shading indicates negative potential. (From "Neuronal Basis of EEG-Waves" by O. Creutzfeldt and J. Houchin. In A. Remond [Ed.], *Handbook of Electroencephalography and Clinical Neurophysiology* [Vol. 2C]. Amsterdam: Elsevier, 1974. Reprinted by permission.) D. Schema of the anatomical arrangement of neurons of the dorsal horn and the expected current flow following their excitation by afferent fibers. Large afferent fibers are shown as thick lines terminating in laminae II–III. At stimulus intensities used in human recordings, few if any of the smaller afferent fibers shown would be stimulated. (Adapted from Wall, 1964.)

ventral regions of the neuron, the cell bodies and axons—a positivity ventrally. A quantitative model of this situation is shown in Figure 1-5C, and Figure 1-5D is a summary of the model for dorsal horn neurons. That the experimentally observed dipolar potential field is similar to that predicted by Gasser and

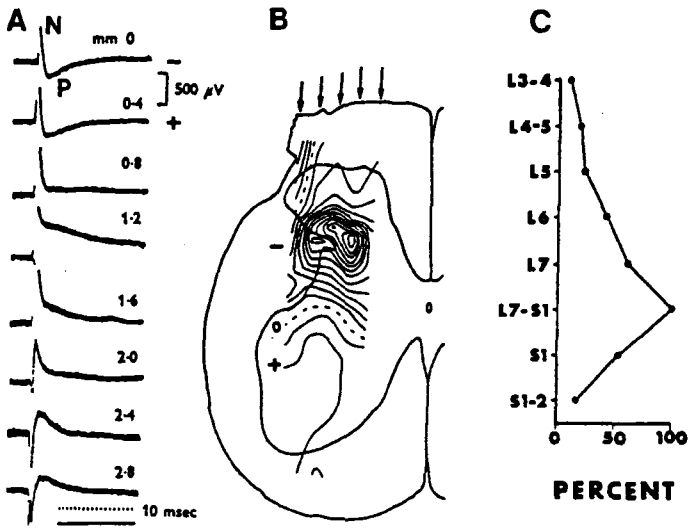

Figure 1-6. Potentials generated in the dorsal horn. A. Potentials recorded in spinal cord at indicated depths from the dorsal surface, to stimulation of cat superficial peroneal nerve. Note polarity inversion of the N wave to a positive potential at a depth of about 2 mm, corresponding to laminae IV–V. (From "Central Pathways Responsible for Depolarization of Primary Afferent Fibres" by J. C. Eccles, P. G. Kostyuk, and R. F. Schmidt. *Journal of Physiology* [London], 1962, 161, 237–257. Reprinted by permission.) B. Isopotential contour map showing the topography of the N wave dorsally and its polarity-inverted counterpart ventrally. C. Longitudinal distribution of N-wave amplitude, plotted as a percentage of maximum. L = lumbar, S = sacral. Both B and C depict stimulation of monkey sural nerve. (From "Spinal Cord Potentials Evoked by Cutaneous Afferents in the Monkey" by J. E. Beall, A. E. Applebaum, R. D. Foreman, and W. D. Willis. *Journal of Neurophysiology*, 1977, 40, 199–211. Reprinted by permission.)

Graham has been demonstrated by many investigators (e.g., Figures 1-6A, 1-6B).

The change in polarity from the region of negative current sinks to positive current sources is called a "polarity inversion," and the point at which the potential changes from one polarity to the other is often regarded as a sign that the electrode is in close proximity to the source. That assumption is correct for potential fields generated by a single localized source, but it can be incorrect in the case of fields generated by multiple sources. In the latter case, the zero potential line is simply the point at which activity from the two sources sums to zero, and it need have no particular spatial significance.

Finally, we need to know the distribution of active neurons longitudinally in the cord. The incoming dorsal root fibers split into ascending and descending branches, which travel some distance while giving off collaterals to the dorsal horn interneurons. Figure 1-6C shows the longitudinal extent of the N wave; while the potential is largest at the level of entry of the dorsal roots corresponding to the peripheral nerve stimulated, it can be recorded for some distance along the cord. Thus the N wave is generated by a long, narrow sheet of dorsal horn interneurons.

In the cat, the A spike and the N wave produce detectable potentials at the surface of the neck (Figure 1-7A); presumably, corresponding potentials can be recorded from the human neck (Figure 1-7B). The surface potentials are smaller by at least an order of magnitude than those recorded directly from the cord, but signal averaging readily allows their recording. The potential field as recorded from the surface of the head and neck has not been studied in detail, but recordings to date suggest that the field is negative over the posterior neck and scalp and positive over the frontal scalp and neck, in agreement with the postulated field shown in Figure 1-7C.

In the somatosensory system, the dorsal horn neurons are the initial site of generation of PSPs. Graded depolarization of the dendrites spreads into the cell body, and if the magnitude of the EPSP is large enough, a spike is generated. The potential fields generated by action potentials and graded PSPs are not essentially different; in either case, depolarization is associated with a local negative sink and with a positivity near the region of the neuron that provides source current. The N wave (or its positive counter-

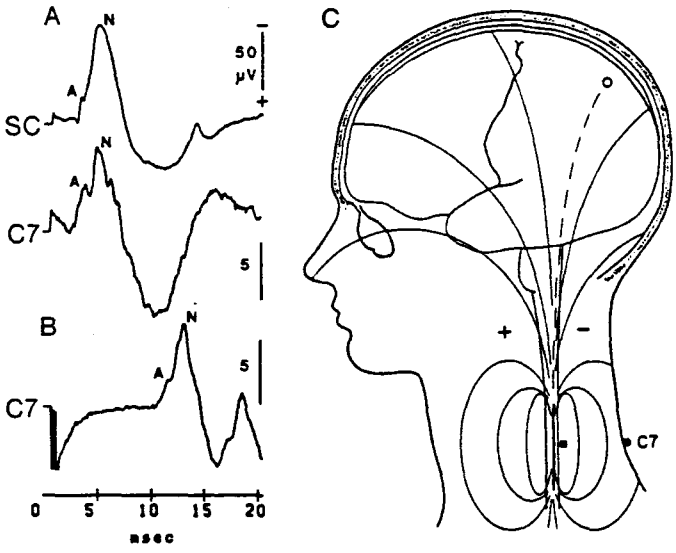

Figure 1-7. Potentials recorded simultaneously in a cat from the surface of the spinal cord (SC, upper trace) and from the surface of the neck over the C_7 vertebra. B. Potentials recorded in a human from the surface of the neck over the C_7 vertebra. For both A and B, reference electrode is on frontal scalp; negative at spinal electrode is upward. C. Postulated potential field produced by excitation of dorsal horn neurons; the field is negative over the posterior neck and scalp and positive over the anterior neck and scalp. For clarity, the most intense parts of the field are omitted.

part in the ventral cord) is thus a summation of EPSPs and action potentials, but the relative contribution of each type of potential to the overall waveform is not known. Most of the primary afferent fibers entering the spinal cord terminate within a few segments, but some of them, particularly the larger ones carrying information from cutaneous receptors, ascend in the ipsilateral dorsal column and terminate in the cuneate nucleus.

The Cuneate Nucleus

The neurons of the cuneate nucleus tend to be oriented vertically with their dendrites extending dorsally. The incoming dorsal column fibers turn ventrally and make dense synaptic contacts with the dendrites (and to a lesser extent the cell bodies) of the relay cells. Hence we might expect the potential field to resemble that generated by dorsal horn neurons. That this is the case has been shown by Andersen, Eccles, Schmidt, and Yokota (1964). Dorsal to the cuneate nucleus, they recorded a negative potential (Figure 1-8A), which they called the "N wave" by analogy with the spinal cord N wave. The N wave polarity is inverted to a positive potential ventral to the nucleus (Figure 1-8B). The extracellular current flow postulated to account for these results is shown in Figure 1-8C; note the similarity to the situation in the dorsal horn. The A spike and N wave of the cuneate nucleus can apparently be recorded from a surface electrode at the base of the skull in cats (Figure 1-9A) and humans (Figure 1-9B); in both species, the potentials are slightly later than their dorsal horn analogues. The potential field of this activity is not known in detail, but may approximate the form postulated in Figure 1-9C. As in the spinal cord, the responsive neurons are located in a narrow strip at least 10 mm long in the rostrocaudal dimension, and thus generate a distributed dipolar field. The cuneate N wave, like its spinal analogue, is a mixture of the EPSPs and action potentials. Because the initial input to the nucleus is highly synchronous, the initial postsynaptic discharge is often recorded as a spike superimposed on the slower EPSPs (Figure 1-9A). In contrast, the dorsal horn N wave often appears as a smooth potential, perhaps because there is more temporal dispersion in the arrival of afferent input from the slowly conducting collaterals of dorsal column fibers. The depolarization of cuneate cell bodies then proceeds into their axons, which constitute the medial lemniscus.

The Medial Lemniscus

An electrode placed in the cat thalamus near the termination of lemniscal fibers records a positive-negative spike potential (Figure 1-10, upper left, arrow) reminiscent of the A spike in the spinal cord. In humans the surface potential field of the lemniscal volley is not well characterized, but in monkeys it is recorded as a positive potential from the dorsal surface of the brain (Arezzo, Legatt, & Vaughan, 1979). Recall that a compound action potential is recorded at or beyond the termination of the nerve as a positive potential (see Figure 1-1). The same phenomenon has been demonstrated in fiber tracts of the CNS (Schlag, 1973). As a rule, it may be supposed that afferent volleys in ascending sensory pathways will be recorded as positive potentials over most of the scalp. The lemniscal volley now produces a strong depolarization of neurons in the thalamic ventroposterior nucleus.

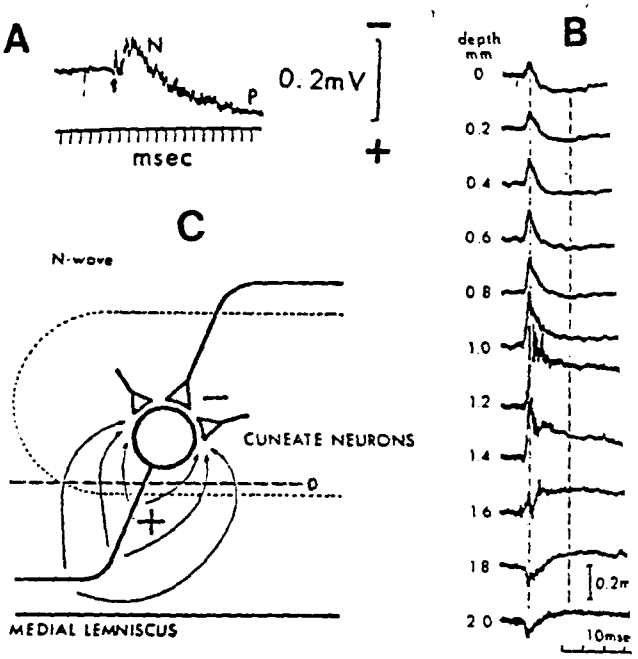

Figure 1-8. Potentials generated in cuneate nucleus. A. Potentials recorded from surface of cat cuneate nucleus to superficial radial nerve stimulation. Arrow indicates afferent volley in dorsal column fibers. B. Potentials evoked by median nerve stimulation at indicated depths from the surface of the cuneate nucleus. C. Postulated basis of N wave recorded in cuneate nucleus to afferent input from dorsal column. Relay neurons are depolarized; the current flowing into this area is indicated by the arrow, and generates a negativity superficially (the N wave) and a deep positivity. Afferent fibers are shown making contact with cuneate cell bodies; the majority of synaptic contacts are probably on the dendrites. In either case the dorsalmost portion of the cell is assumed to be depolarized, producing a negative potential field at and dorsal to the region of depolarization. In this diagram, the back of the neck is upward, and the head is to the left. (Adapted from Andersen, Eccles, Schmidt, and Yokota, 1964.)

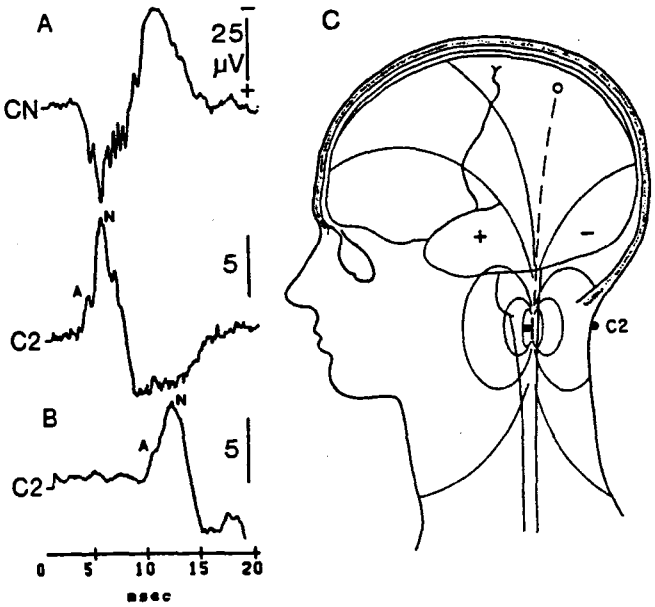

Figure 1-9. Potentials generated in cuneate nucleus. A. Upper trace: Recording 1 mm ventral to cat cuneate nucleus (CN), location indicated by square in human figure at right; dorsal to nucleus, the spike potential was negative and was superimposed on a slower negativity (the cuneate N wave). Lower trace: Simultaneous recording from the skin over the C_2 vertebra illustrating the surface-recorded cuneate N wave. (Adapted from Allison and Hume, 1981.) B. Similar surface recording from human C_2 vertebra showing presumed cuneate N wave. C. Postulated potential field produced by excitation of cuneate neurons. Potential is negative over posterior neck and scalp and positive over anterior neck and scalp. For clarity, the most intense parts of the field are omitted.

The Thalamic Ventroposterior Nucleus

Scheibel and Schiebel (1966) investigated the structure of neurons in the ventroposterior (VP) nucleus of the thalamus (Figure 1-11A). The arborizations of lemniscal afferents terminate on dendrites of the thalamo-cortical relay cells. While there is variation in the arrangement of these cells and their processes, their general orientation may approximate that shown in Figure 1-11B. Depolarization of the dendrites would produce approximately the potential field illustrated.

Andersen, Brooks, Eccles, and Sears (1964) investigated the potentials generated in the VP nucleus by stimulation of peripheral nerves (see Figure 1-10, upper left). The lemniscal volley was followed by a slower negative potential, which they called the "N wave" by analogy with the spinal and cuneate N waves. The N wave reflects the depolarization of VP neurons and would thus correspond to the negative portion of the field assumed in Figure 1-11B. They did not record the potential field in the thalamus, but Arezzo *et al.* (1979) have done so (see Figure 1-10, lower). In and ventral to the VP nucleus, a lemniscal volley (labeled q in track A-A′ and B-B′) was followed by a negative potential on which a negative spike was superimposed (r in track B-B′). Dorsal to the VP nucleus, a positive spike superimposed on a positive wave is seen at the same latency (s in tracks A-A′ and B-B′). If this activity is assumed to be postsynaptic, the potential field approximates the open field pre-

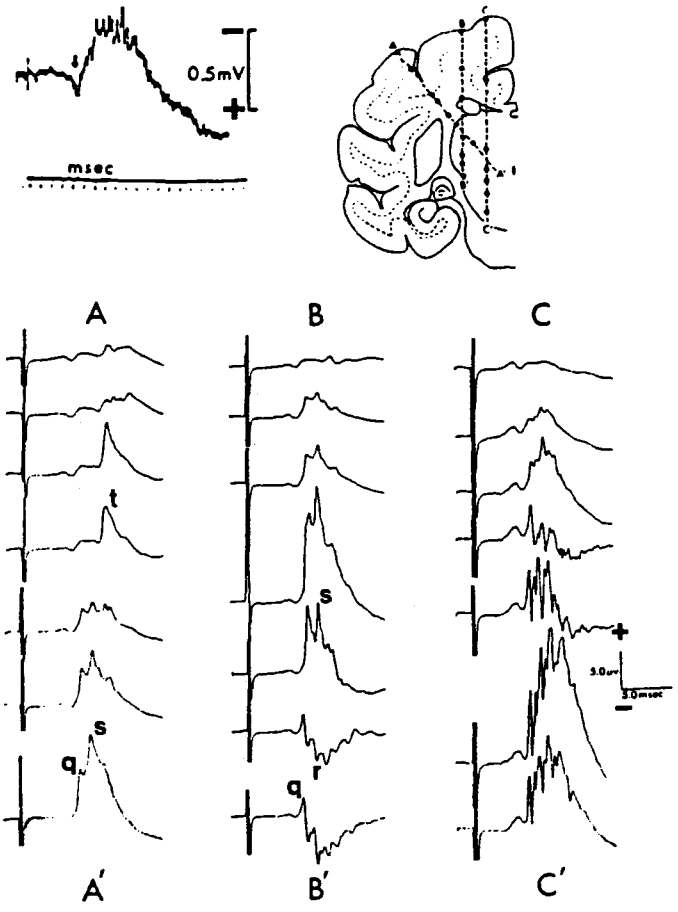

Figure 1-10. Potentials generated in ventroposterior (VP) thalamus. Upper left: Potentials recorded in VP to cat median nerve stimulation. Diphasic (arrow) and negative lemniscal spike is followed by slower negative potential (VP N wave) with superimposed spikes. (From "The Ventro-Basal Nucleus of the Thalamus: Potential Fields, Synpatic Transmission and Excitability of Both Presynaptic and Postsynaptic Components" by P. Andersen, C. M. Brooks, J. C. Eccles, and T. A. Sears. *Journal of Physiology* [London], 1964, 174, 348–369. Reprinted by permission). Lower: Potentials evoked by monkey median nerve stimulation and recorded along electrode tracks shown at upper right. (Adapted from Arezzo, Legatt, and Vaughan, 1979.)

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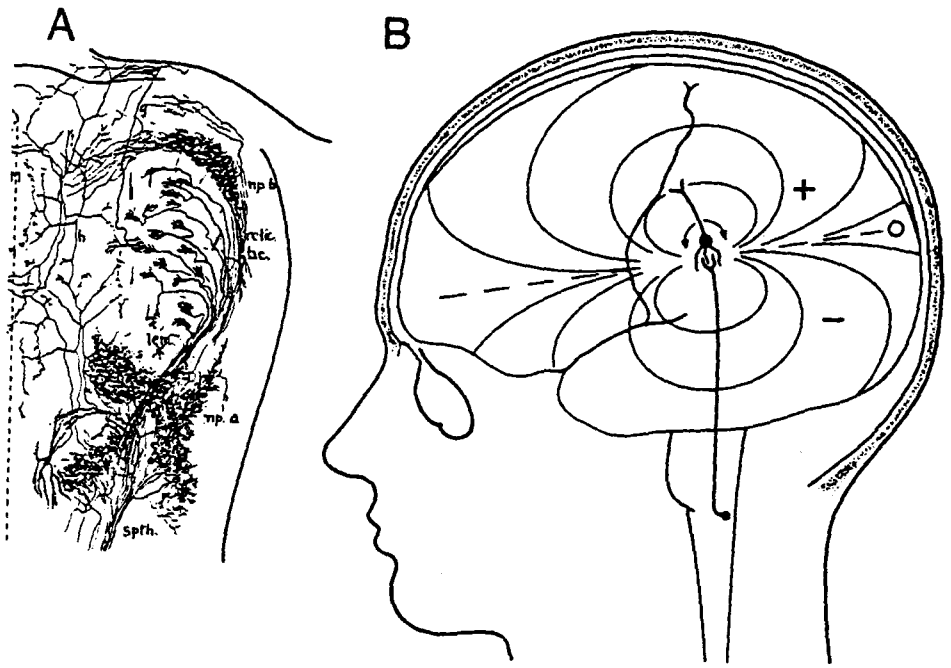

Figure 1-11. Anatomy and electrogenesis of ventroposterior (VP) thalamus. A. Horizontal section showing bushy arborizations of lemniscal (lem) afferents terminating on dendrites of VP relay neurons (g). (From "Patterns of Organization in Specific and Nonspecific Thalamic Fields" by M. E. Scheibel and A. B. Scheibel. In D. P. Purpura and M. D. Yahr [Eds.], *The Thalamus*. New York: Columbia University Press, 1966. Reprinted by permission.) B. Postulated potential field produced by depolarization of VP relay neurons. For clarity, the most intense parts of the field are omitted.

dicted in Figure 1-11B. However, Arezzo *et al.* (1979) interpreted these potentials as being of lemniscal origin, concluded that discharge of VP neurons could not be recorded outside the nucleus, and suggested that the orientation of these neurons leads to the generation of a closed field. The data of Figure 1-11B suggest that the third alternative, an open–closed field, may be the best approximation. Note that an inner core of negativity in and ventral to the VP nucleus is surrounded laterally, dorsally, and medially by a shell of positivity resembling the open–closed field of Figure 1-2 (right). Until detailed three-dimensional plots of the potential field in the region of the VP nucleus are available, it is not possible to choose among these alternatives. The point to be emphasized here is that structures such as thalamic and brain stem nuclei may generate potential fields that are smaller and more complex than the relatively simple open fields considered thus far, and correspondingly more difficult to record at a distance. Whatever the reason, there is as yet no agreement among ERP researchers whether VP and other thalamic potentials can be recorded from the surface of animals or humans. The afferent volley in axons of VP neurons now proceeds via the internal capsule into somatosensory cortex.

Somatosensory Cortex

The thalamo-cortical afferent volley is recorded at or near the cortical surface as a positive potential (Figure 1-10, t in track A-A′), as would be expected from earlier discussion. These fibers terminate mainly in layer IV of somatosensory cortex, where they make synaptic contact on the lower portion of the apical dendrites of pyramidal cells and on the numerous stellate cells that give sensory cortex its characteristic striped appearance. The stellate cells, in turn, are thought to terminate on pyramidal cells. This is a more complicated neuronal connectivity than has been considered previously. However, because the stellate cells have randomly oriented dendrites and axons, their potential fields are usually assumed to cancel. In contrast, the pyramidal cells are oriented in parallel, with their large apical dendrites extending upward into the molecular layer (Figure 1-12A). Depolarization of pyramidal cells approximates Lorente de Nó's open-field model, which assumes that source current is drawn from apical dendrites. But one might wonder whether the axons also serve as current sources in the same manner as the regions on either side of the depolarized portion of an axon serve as sources. Calculations of the potential field generated by a single pyramidal cell indicate that the axon is in fact a weak current source (Figure 1-12B). However, the negative sink potentials are much stronger: for a population of neurons, the algebraic summation of source and sink potentials leads to a net negative potential throughout the region in and ventral to the cell bodies.

An example of this activity in the monkey is shown in Figure 1-13A. The potentials in the latency range of 6–10 msec reflect activity of subcortical structures as discussed above. A few milliseconds later, a positive potential (p) is seen at the surface and superficial layers of cortex, while simultaneously a negative po-

tential (n) is recorded in deeper layers of cortex and white matter. A few milliseconds later still, the potential field reverses, the superficial layers becoming negative and the deeper layers positive. The generally accepted explanation of this sequence of events was provided by Bishop and Clare (1952). Their recordings were made in cat visual cortex, but there is good evidence that the same events also occur in somatosensory and auditory cortex in response to an afferent thalamo-cortical volley (Landau & Clare, 1956, Towe, 1966). Bishop and Clare (1952) concluded that the superficial-positive–deep-negative field is produced by depolarization of pyramidal cells at or near the cell bodies, while the superficial-negative–deep-positive field is produced by slightly later depolarization of the apical dendrites. The earlier field is thus similar to the models of Figure 1-2 (left) and Figure 1-12B, while the later field approximates the model of Figure 1-5C and is similar to the spinal and cuneate N-wave fields.

Figure 1-13B shows recordings from the cortical surface of a human. Location 5 is just posterior to the central sulcus, as in the monkey recording, and sees a positivity (P25) followed by a negativity (N35). This sequence corresponds to the monkey p-n sequence of Figure 1-13A; in both species, the source is thought to be located in area 1 in the crown of the postcentral gyrus (Allison, 1982; Arezzo *et al.*, 1979; see Figure 1-14A). In addition, note that at electrodes 6 and 7 (located a few mm posterior and lateral to 5), P25 is smaller and N35 is not identifiable, while other potentials labeled N20 and P30 are seen. Anterior to the central sulcus, P20 and N30 potentials are seen. To account for the N20–P30 and P20–N30 potentials, it is necessary to postulate at least one source in this region of cortex, in addition to the area 1 source.

One possibility is illustrated in Figure 1-14A. This model assumes a positive-negative sequence analogous to the P25–N35 sequence of area 1, but generated in area 3b and thus tilted by about 90°, due to the location of this area in the posterior bank of the central sulcus. If this is the case, P20–N30 would be recorded at the surface of and anterior to 3b, while posterior to 3b its polarity-inverted deep counterpart

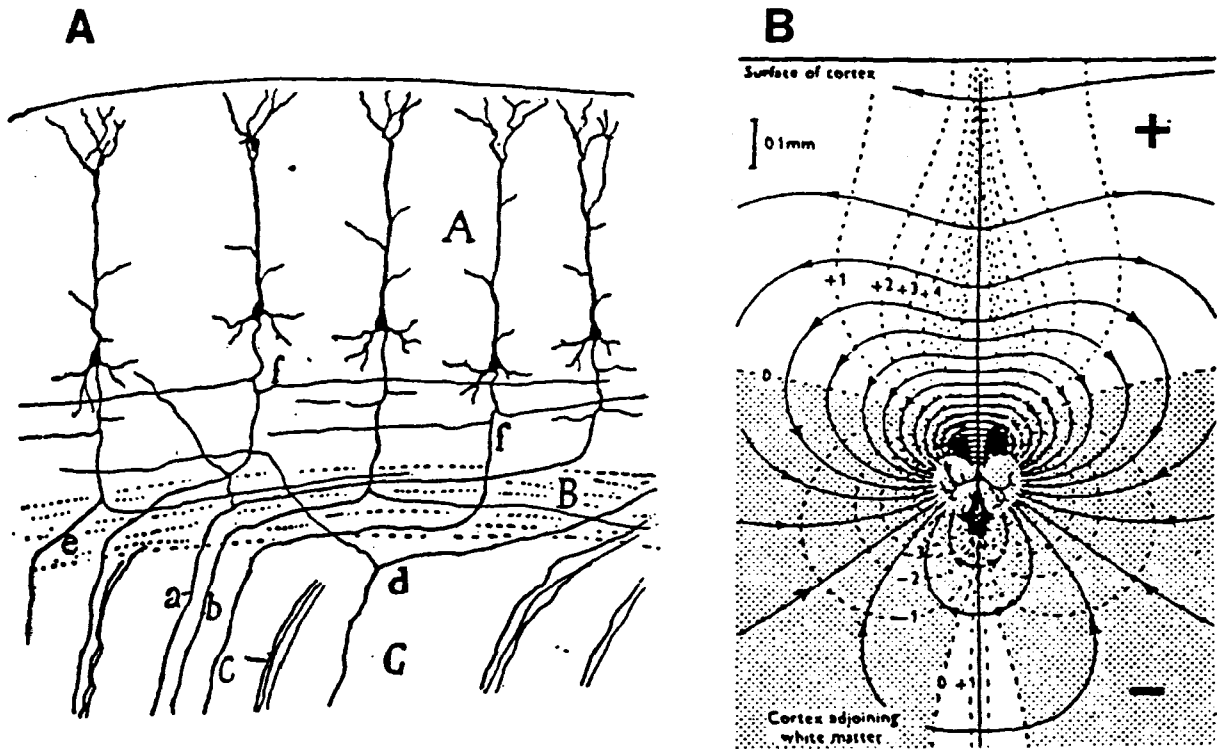

Figure 1-12. Anatomy and electrogenesis of cerebral cortex. A. Cortical pryamidal cells (A) with large dendrites extending to the cortical surface and axons (f) entering white matter (B). (From *Neuron Theory or Reticular Theory?* by S. Ramón y Cajal. Madrid: Instituto Ramón y Cajal, 1954. Reprinted by permission.) B. Calculated extracellular potential field generated by depolarization of the cell body of a pryamidal cell. Solid lines indicate current flow; broken lines are isopotential lines. For clarity, the most intense parts of the field are omitted. Shading indicates negative potential. Evidence suggests that thalamocortical fibers terminate mainly on the basal portion of apical dendrites; if this is the primary source of synaptic input, the region of maximal depolarization would be somewhat higher than shown. (From "Neuronal Basis of EEG-Waves" by O. Creutzfeldt and J. Houchin. In A. Remond [Ed.], *Handbook of Electroencephalography and Clinical Neurophysiology* [Vol. 2C]. Amsterdam: Elsevier, 1974. Reprinted by permission.)

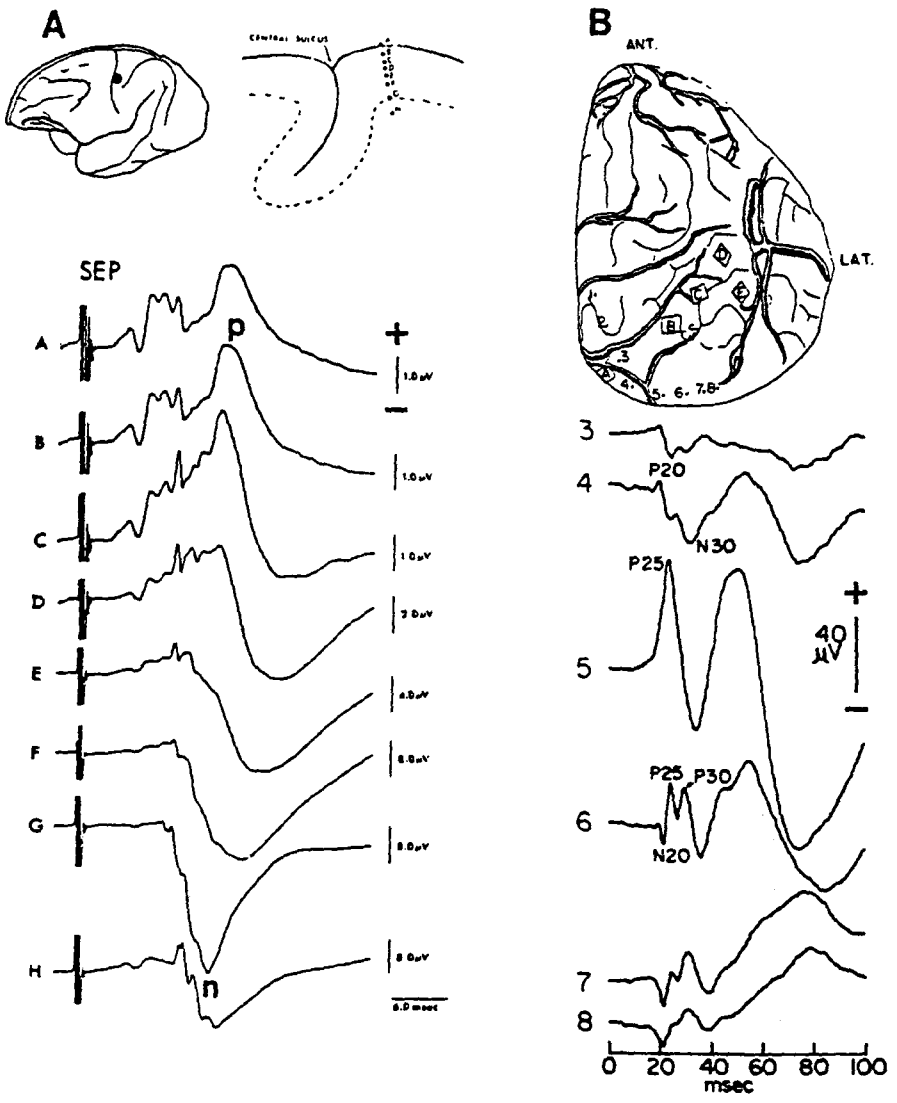

Figure 1-13. A. Potentials generate in monkey somatosensory cortex. Sur face positive potential (p) inverts to negative potential (n) deep in cortex Earlier potentials are of subcortica origin. Right median nerve stimula tion. Adapted from Arezzo, Legatt and Vaughan, 1979.) B. Potentials re corded from surface of right hemi sphere of human somatosensory cor tex to left median nerve stimulation Lettered tickets indicate locations of cortical stimulation: A, wrist and fin ger flexion; B–E, various mouth move ments. CS, central sulcus. (Adapted from Allison, Goff, Williamson, and VanGilder, 1980.)

(N20–P30) would be seen. In other words, all these potentials are postulated to result from the sequential activation of two sources: first, the area 3b source beginning at about 20 msec, then the area 1 source beginning at about 25 msec. Whether or not the details of this model prove to be correct, these recordings illustrate that concurrent activation of nearby cortical regions produce complex potential fields that can be difficult to disentangle, both spatially and temporally.

These potentials are also seen in scalp recordings (Figure 1-14B). Comparison of these recordings with cortical surface recordings of the same activity (see Figure 1-13B) exemplifies the problem that the increased distance from the active tissue and the higher resistivity of the skull degrade scalp recordings in two ways:

1. Scalp potentials are much smaller that their cortical counterparts. Other things being equal, the signal-to-noise ratio of scalp recordings in correspondingly poorer. This is not a major problem, because additional averaging can be used to improve the signal-to-noise ratio.

2. In cortical surface recordings, it is possible to record the area 3b and area 1 potentials in relative isolation at some locations, but scalp recordings show mixtures of both types of activity at most locations. That is, spatial resolution is poorer in scalp recordings. This is a problem because the greater spatial overlap of potentials from different sources decreases the ability to study a source in isolation.

The hypothesized area 3b source should produce an open field, with the zero potential line more or less

parallel to the central sulcus and with the major axis of the dipole orthogonal to it. The scalp field shown in Figure 1-14B, plotted at the latency corresponding to the peak of the N30 and P30 potentials, conforms closely to the predicted field. However, the similarity does not by itself prove that the field is generated in area 3b. It is possible that separate generators in motor cortex and somatosensory cortex independently produce the N30 and P30 potentials, respectively, and indeed some investivators favor this explanation (e.g., Desmedt & Cheron, 1980). In our opinion, the N30–P30 field shown in Figure 1-14B is more plausibly explained by a single somatosensory cortex source than by two simultaneously active sources in motor and somatosensory cortex that produce surface fields of opposite polarity (Allison, 1982). However, it is true that surface recordings alone (whether from the cortex or the scalp) do not provide unambiguous answers regarding the number, location, and orientation of sources contributing to a given surface potential field.

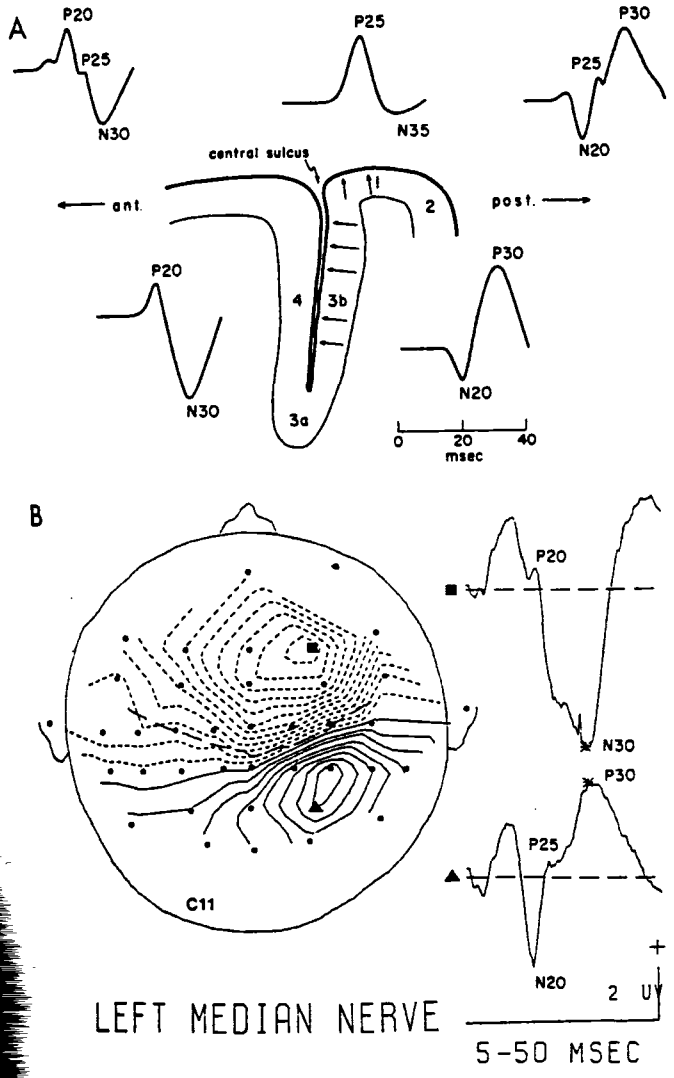

Figure 1-14. A. Location and orientation of sources postulated to account for potential fields recorded from the cortical surface and scalp of humans during initial activation of sensory-motor cortex by median nerve stimulation. Drawing is a sagittal section through the hand area of human sensory-motor cortex in the left hemisphere; note large amount of cortex buried in the central sulcus relative to the amount occupying the surface. B. Potential field recorded from scalp to left median nerve stimulation, plotted at peak (asterisk) of P30 and N30 potentials. Traces are from F_4 (square) and P_4 (triangle); dashed line is approximate location of the central sulcus.

IMPLICATIONS FOR PSYCHOPHYSIOLOGICAL ERP RESEARCH

We can now point, perhaps with equal amounts of pride and alarm, to some generalizations concerning the value and limitations of surface ERPs as measures of human CNS activity. The reader is, we hope, convinced that potential fields generated by neuronal activity and recorded at the surface of the body are not mysterious or unmanageable in any fundamental way. Such potential fields may be described quantitatively and can be accounted for in terms of characteristics of the electrical sources and characteristics of the conductive medium in which they are recorded—that is the number, location, orientation, and synaptic connectivity of the neural elements involved, and the properties of the human brain and body as electrically conductive media.

Nevertheless, as measures of CNS events occurring at a given instant or as measures of changes in such events over time, surface ERPs are limited in a number of important respects that have implications for ERP research:

1. Because of superposition, the extracellular potentials from all neuronal transmembrane currents existing at a given instant summate at every point in and on the surface of the head and body. Thus, surface ERPs are a *statistical aggregate* in which the contribution of the transmembrane currents associated with each active neuron are combined with those from all other active neurons to yield the surface potential field. Moreover, the contribution of each neuron (and each gross anatomical structure) can lose its identity in the summation. Just as there is no way of answering the question "How many different values were added to yield the sum 43, and what are they?", there is no way to determine from the instantaneous potential difference between two electrodes the number of distinct sources that have contributed to that potential

difference and their relative contributions. Note that we are *not* saying that it is in principle impossible to determine the sources of surface ERPs; a number of experimental and theoretical approaches to this problem are being actively investigated (for reviews, see Vaughan, 1982; Wood, McCarthy, Squires, Vaughan, Woods, & McCallum, 1984). Rather, what we wish to emphasize is that neither the number nor the location of sources is directly evident in surface ERPs.

2. Because extracellular potential fields (and hence surface ERPs) depend heavily upon the orientation of active nerve cells and cell groups, the locus of synaptic activation, the degree of temporal and spatial synchronization, and the spatial relationship of the active tissue to the recording electrodes, they are likely to be *incomplete* and *biased* measures of CNS activity. They are incomplete in the sense that not all neural events occurring at any given time contribute significantly to surface potentials. They are biased in the sense that some cells, by virtue of their location, orientation, and other biophysical characteristics listed above, are more likely than other cells to contribute significantly to surface potentials.

3. Because of the aggregate, incomplete, and biased character of surface ERPs, we might anticipate that the mapping between ERP components and psychological processes will not be straightforward. Some of the neural events that mediate a given psychological process may not contribute to surface ERPs, and those that do may contribute to a number of ERP components. Similarly, a given ERP component may be contributed to by neural events that mediate a number of different psychological processes. Even the simplest surface ERP we have discussed, the peripheral nerve volley, is an amalgam of potentials that are generated by afferent neurons from a variety of receptor types in skin, joints, and muscles, and that contribute to a variety of somatosensory functions. The attempt to separate the compound action potential into parts having different functional characteristics won Gasser and Erlanger the Nobel Prize in 1944, but unresolved issues are still being investigated (Dorfman, Cummings, & Leifer, 1981). Since even the simplest surface ERP does not map in a one-to-one manner onto psychological processes, we should be cautious about attributing such one-to-one mappings to more complex ERPs from the CNS. This issue is discussed further in the next section.

4. Even if we knew in exquisite detail both the specific neurons that contribute to a given surface ERP and the relative magnitudes of their contributions, the surface ERP would provide little or no information concerning the information-processing operations at the neuronal level performed by the cells in question. Consider extracellular potentials generated by the lateral geniculate nucleus (LGN) in response to a patterned visual stimulus. Such potentials would be generated by LGN cells having on-center–off-surround receptive fields, as well as those having off-center–on-surround receptive fields. Similarly, extracellular potentials would be generated both by "X-cells" having predominately tonic or sustained responses to visual stimulation, as well as "Y-cells" having predominately phasic or transient responses (Stone, Bogdan, & Leventhal, 1979). ERPs recorded under such conditions (either from the LGN or from the surface) would indicate some form of activity in the cells in question, but they would not indicate the information-processing operations performed by the neurons that contribute to that activity.

On the other hand, useful information can be gained if the generators of surface ERPs are known, even if we cannot specify the cellular information-processing operations being performed. In clinical applications, for example, ERPs are used simply as test signals, in much the same manner that an electronics repairman traces a signal from a phonograph cartridge (receptor) to the movement of a loudspeaker (motor response). Knowledge of the place in the circuit where the signal is absent or distorted is useful even in the absence of a functional understanding of the signal.

5. Implicit in the previous discussion is the conclusion that the polarity of a potential conveys no information about its neurophysiological basis. Even if the orientation of neurons is similar and their activity is recorded in the same manner, the polarity of the potential can differ, depending on the portion of the cell activated. We have seen that dorsal horn and cortical neurons are both arrayed in rows, with their dendrites extending upward and their axons downward. Yet excitation of these neurons by an afferent volley produces initial potentials of opposite polarity when recorded from the surface of these structures. The difference is that the distal portion of the spinal dendrites is depolarized, whereas the proximal portion of the cortical dendrites is depolarized; hence, in the two structures, the spatial relationship of source and sink is reversed. Two conclusions follow:

a. The labels we attach to potentials are arbitrary. It is an accident of spinal anatomy, for instance, that the dorsal surface of the cord is more accessible than the ventral surface, and thus accidental that the excitation of spinal interneurons is recorded as a negativity and is often labeled the "N wave." This is a useful label, but it should not be taken to imply that the negative sink potential is somehow more real or important than the positive source potential that is its necessary counterpart. For this reason, some investigators (e.g., Beall, Applebaum, Foreman, & Willis, 1977) avoid the label "N wave" and use the neutral term "phase" to refer to this activity as recorded with either polarity. In human recordings, it is recommended (Donchin, Callaway, Cooper, Desmedt, Goff, Hillyard, & Sutton, 1977) that peaks of an ERP waveform be labeled according to their polarity and average peak latency in milliseconds (e.g., Figure 1-

14). This is a useful nomenclature—in most respects, it is preferable to other labeling systems—as long as it is kept in mind that the polarity label reflects the particular recording locations used.

b. Although we have only discussed action potentials and EPSPs, the potential fields produced by IPSPs can be readily understood from the same principles. An IPSP is a *hyperpolarizing* graded potential that is due to an outward flow of current in the vicinity of the synapse and inward current flow over the remainder of the cell (i.e., current source and sink, respectively). IPSPs are accompanied by local extracellular positive potentials and distant negative potentials, just the opposite of EPSPs. In the absence of additional information, such as intracellular recordings, it is not possible to infer whether a positive potential reflects local IPSPs or distant EPSPs. This is unfortunate, because most human ERPs later than the initial afferent volley consist mostly if not entirely of summated PSPs rather than summated action potentials (Goff, Allison, & Vaughan, 1978). For such potentials, ERP and single-unit studies in animals of the presumed counterpart of the human potential are required to determine whether the surface recording reflects excitatory or inhibitory events, or both. This is a major undertaking, but to keep the problem in perspective, consider that the year in which this chapter is being written (1983) marks the 50th anniversary of Gasser and Graham's (1933) study of spinal cord potentials. Despite intense investigation by many excellent neurophysiologists, the excitatory (N wave) and inhibitory (P wave) properties of these potentials are still being clarified (Willis & Coggeshall, 1978).

6. Extracellular potentials from different sources often overlap in time and space. Gasser and Graham (1933) were aware of this problem in trying to separate the spinal cord N and P waves: "Now, whatever interpretation may be put on the positive wave, the presumption is that the processes producing it do not start at the end of the negative wave but at some time earlier; and from this it follows that the activity producing the negative wave . . . must be in existence longer than the wave itself" (p. 308). Spinal cord neurophysiologists have used several techniques to try to separate the two potentials. One technique is to asphyxiate the animal. Since different neural structures can have different sensitivities to lack of oxygen, it is often possible to eliminate one potential while leaving the other more or less intact. Gelfan and Tarlov (1955), for example, demonstrated that the P wave was abolished before the N wave (Figure 1-15), and it can be seen (at 2'30", for example) that the N wave has a longer duration than appears to be the case under normal conditions, as Gasser and Graham (1933) surmised. Eccles, Kostyuk, and Schmidt (1962) also assumed that the neural events underlying the N wave outlasted the observable wave itself. In attempting to map the potential field of the P wave in the cord and hence to infer its origin (see Figure 1-6A), they measured the P wave late in its course "so as to avoid interference by the initial waves" (p. 243).

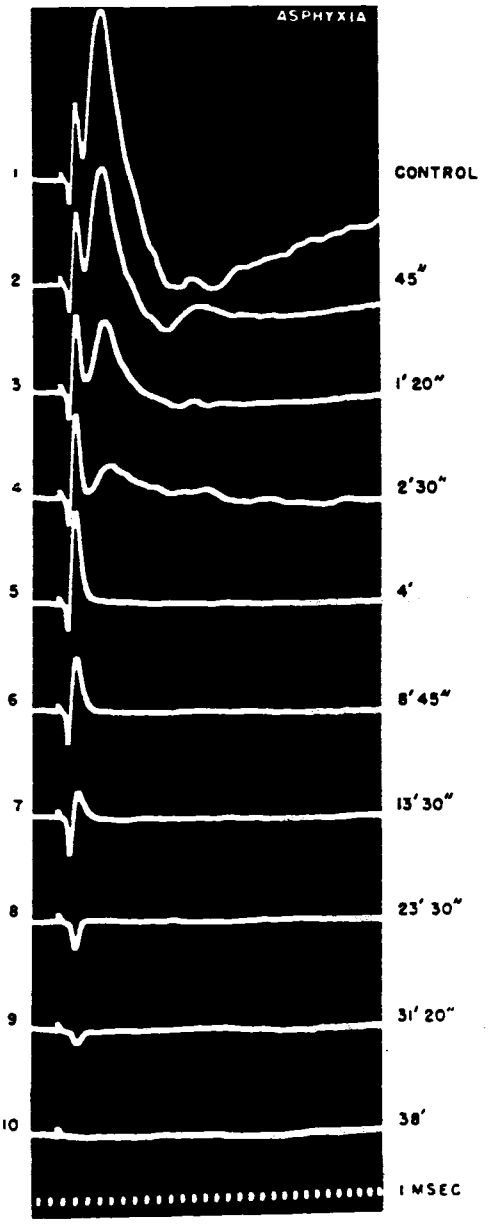

Figure 1-15. Effects of asphyxia on spinal cord potentials in a dog anesthetized with Dial. Recording from the L_7 cord segment to stimulation of the S_1 dorsal root; negative is upward. Note sequential abolition of P wave, N wave, A spike, and positive potential preceding the A spike. (From "Differential Vulnerability of Spinal Cord Structures to Anoxia" by S. Gelfan and I. M. Tarlov. *Journal of Neurophysiology*, 1955, 18, 170–188. Reprinted by permission.)

In human recordings, it is even more difficult to obtain undistorted measurements of potentials. The manipulation used by Gelfan and Tarlow (1955) is ill-advised, and the method of Eccles *et al.* (1962) can be

criticized on the grounds that measuring potential B late in its course to avoid distortion by potential A only increases the distortion due to potential C. Multivariate statistical analysis and other quantitative techniques have been used to attack this problem (e.g., Donchin & Heffley, 1978), but as yet there is no consensus regarding a solution.

7. It is often tempting to assume that the generators of surface ERPs lie in brain structures directly underneath the region where the surface ERP is maximal in amplitude. Such an assumption can be correct, but it need not be. For example, the somatosensory P20–N30 and N20–P30 potentials shown in Figure 1-14 are largest at scalp locations well anterior and posterior to somatomotor cortex. Another example is the ERP generated in visual cortex by a reversing checkerboard pattern (Figure 1-16). When the pattern is viewed centrally (Figure 1-16A, left), a positive potential (P100) is largest at the midline in the occipital area. With stimulation of the left or right half-fields (Figure 1-16A, center and right, respectively) that project anatomically to visual cortex of the contralateral hemisphere, P100 is largest over the ipsilateral hemisphere rather than the contralateral hemisphere, as might be expected. These results can be explained satisfactorily (Barrett, Blumhardt, Halliday, Halliday, & Kriss, 1976; Blumhardt & Halliday, 1979) by considering the location of human visual cortex in the posterior pole of the occipital lobe and extending into the mesial surface (Figure 1-16B).

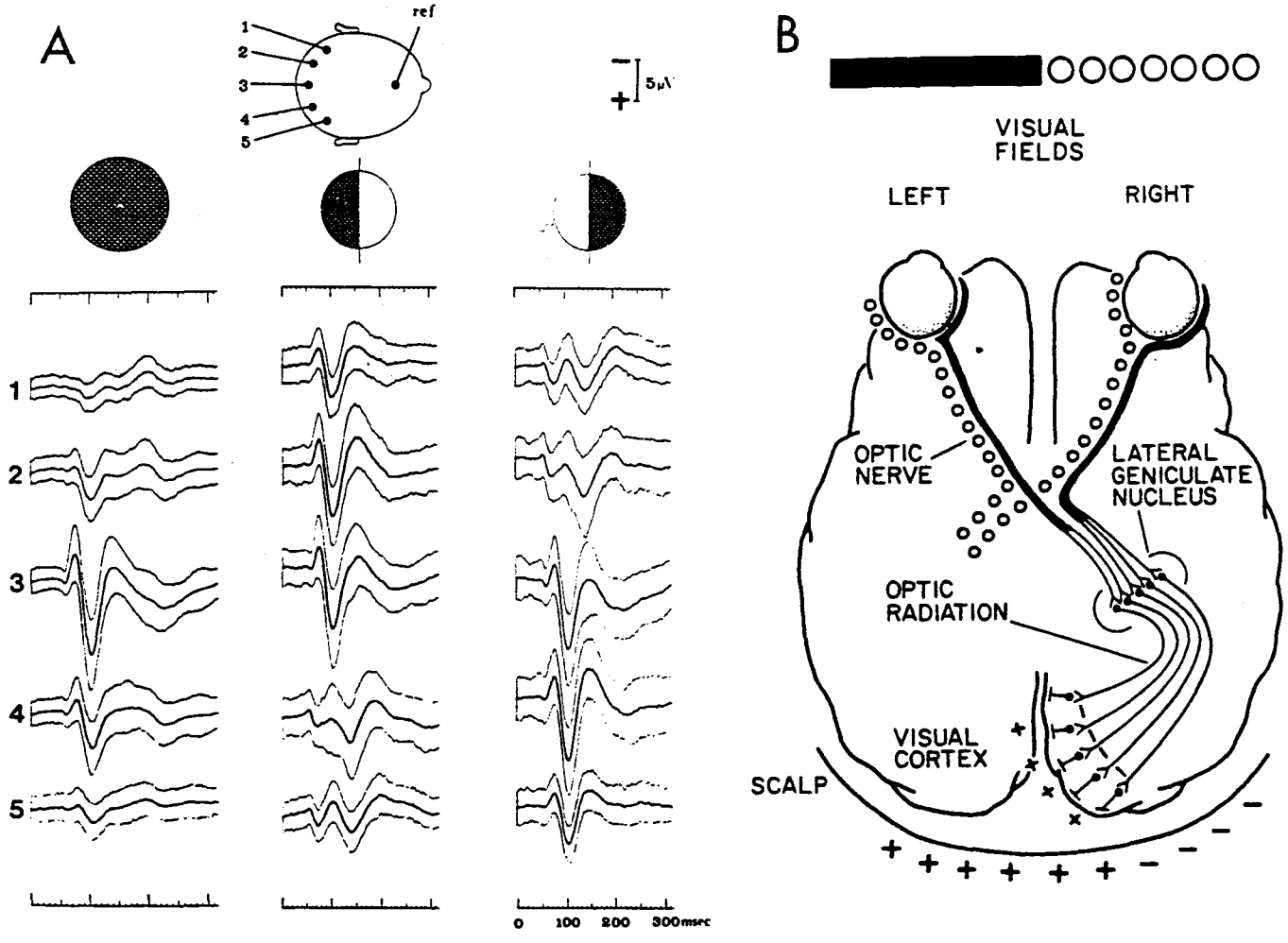

Figure 1-16. Anatomy and electrogenesis of visual cortex. A. Potential fields recorded over human occipital scalp to 2/sec reversal of a checkerboard visual stimulus. Responses to full-field (left), left half-field (center), and right half-field (right) stimulation. Note that largest P100 is recorded at locations ipsilateral to the stimulated half field, with polarity inversion at contralateral locations. Grand average of 50 normal subjects; thick line is mean waveform; thin lines are the standard deviation. (Adapted from Blumhardt and Halliday, 1979). B. Outline of human visual pathway and postulated location of dipole generators in visual cortex to account for the left half field scalp topography in A. Adapted from Barrett, Blumhardt, Halliday, Halliday, and Kriss, 1976 and Kuffler and Nicholls, 1976.)

When a single hemisphere is activated by a visual stimulus in the opposite half-field, the resulting equivalent dipole points toward the opposite hemisphere and thus produces the largest potential over that hemisphere. Full-field stimulation activates both hemispheres and produces the algebraic summation of the two half-field responses. Thus, when the net orientation of active tissue is not perpendicular to the surface of the head, ERP amplitude maxima can occur in scalp regions distant from the active regions of the cortex, including locations over the opposite hemisphere. This has obvious implications for the study of hemispheric function using ERP measures.

8. For additional discussion of neuronal electrogenesis and the recording of extracellular potential fields, see Creutzfeldt and Houchin (1974), Freeman (1975), Goff *et al.* (1978), Klee and Rall (1977), Llinás and Nicholson (1974), Schlag (1973), Vaughan (1974, 1982), Willis and Coggeshall (1978), and Wood and Allison (1981).

CLASSICAL AND MODERN BUMPOLOGY: IT TAKES A LOT OF GALL TO STUDY PSYCHOLOGICAL PROCESSES USING ERPS

In the late 18th century, Franz Joseph Gall became convinced that specific regions of the brain subserve specific psychological functions, and that it might be possible to obtain objective measurements of the amounts of each function by making physical measurements of the skull. His assumptions and methods grew into the 19th-century practice of phrenology, which was ardently accepted by some but viewed with skepticism by others (Figure 1-17). In our opinion, classical "bumpology" provides an instructive example for us modern bumpologists who attempt to study psychological processes and their neural substrates using ERPs. Our purpose in this discussion is not to make invidious comparisons between contemporary ERP research and a 19th-century pseudoscience. Rather, we believe that consideration of certain parallels between them can stimulate a re-examination of some of our tacit, deeply held assumptions.

Gall was a skilled neuroanatomist who wished to establish a science of "organology," which would be "an anatomy and physiology of the brain that would be at the same time a new psychology" (Ackenknecht & Vallois, 1956). Gall's organology was based on four major assumptions:

1. The mind consists of an interacting set of distinct mental functions, or "faculties."
2. Each mental faculty is mediated by a specific, localized region of the brain, which is the "organ" for that faculty.

Figure 1-17. "Bumpology," etching by George Cruikshank, 1826. (Reproduced by permission of the Historical Library, Yale University School of Medicine.)

3. The amount of each faculty is correlated with the physical size of the corresponding region of the brain.
4. The shape of the cranium conforms closely to the shape of the surface of the brain, such that variations in the size of different mental organs are evident as bulges or bumps on the skull (Figure 1-18).

Let us examine each of these assumptions in turn.

1. Many of the mental faculties hypothesized by Gall were characterized only in anecdotal terms, often from his recollection of unusual traits of schoolmates and acquaintances. It should not be surprising that Gall's faculties have, like 19th-century "faculty psychology" in general, not withstood subsequent critical analysis. However, the idea that the mind consists of distinct mental faculties has recently received increased attention in the cognitive sciences (e.g., Chomsky, 1980; Fodor, 1983). Marshall (1980) refers to Chomsky's recent work as the "new organology," emphasizing its similarities to some of Gall's assumptions.

Figure 1.18. "Craniology," anonymous, circa 1840. (Reproduced by permission of the Historical Library, Yale University School of Medicine.)

2. Although functional localization within the brain was a radical notion in Gall's day, the anatomical and neurophysiological discoveries of the 20th century have demonstrated a striking degree of regional specificity in brain structure and physiology. Those discoveries constitute strong evidence for some form of functional localization, but they leave open the key question of how functions defined at the psychological level map onto brain structures and physiological processes (cf. Kaas, 1982). Different regions of the brain have been shown to differ substantially in their anatomical structure and physiological properties, and damage to different regions produces systematic—in some cases, highly specific—patterns of symptoms. However, such evidence does not imply that functions defined at the psychological level (e.g., "long-term memory," "selective attention," etc.) are "localized" in the sense that each such function is mediated by a relatively restricted, contiguous brain region, as Gall hypothesized. The extent to which a given psychological process is or is not "localized" depends both upon the manner in which the process is characterized and distinguished from other processes, and upon the exact sense of the term "localized" under consideration. It is likely that most functions defined at the psychological level are mediated by neural systems of considerable complexity, involving the cooperative activity of a number of different anatomical structures. The herculean task confronting the cognitive and neural sciences is to identify and characterize such systems—that is, to determine the mapping between the abstract processes hypothesized by cognitive scientists and the struct and functional organization of the brain at the l studied by neuroscientists.

3. Modern neuroscientists rightly balk at G assumption that the amount of a mental faculty strongly correlated with the size of its correspond organ in the brain. One reason is that the assumpt is untestable unless the neural circuits responsible a given psychological process are completely spe fied. Even if such information were available, diff ences in size of the relevant brain structures are pc predictors of differences in functional capabili Cases do exist, however, in which the size of cert brain structures is strongly correlated with the beha ioral capacities to which those structures are thoug to contribute. For example, the inferior colliculi echo-locating bats are large compared to their sup rior colliculi, and the superior colliculi of birds ar conversely, larger than their inferior colliculi. Clos to home, portions of the human temporal lobe a often larger in the left hemisphere than in the rigl (Geschwind & Levitsky, 1968), a difference that reported to be detectable at birth. In nodding asser to such examples, however, we should not lose sigh of the fact that many structures other than the inferio colliculi, superior colliculi, and temporal lobes con tribute significantly to the capacities for echo locatio in bats, for visually guided behavior in birds, and fo language in humans, respectively.

4. The assumption that variations in the size and shape of the brain are associated with variations in cranial morphology is correct only in the crudest terms. Large regional variations in skull shape and thickness can occur without obvious variations in brain size and shape, and cranial measurements are crude even in reflecting such gross structural differences as the "hypertrophied" structures mentioned above.

Thus, each of Gall's four main assumptions is incorrect in important respects, but some of his ideas have important parallels in the contemporary neurosciences. Two such parallels are particularly instructive for psychophysiological ERP research.

The first, and more superficial, parallel concerns the nature of the dependent variables employed. Whereas Gall measured the size and location of physical bumps on the skull, we measure the size (amplitude), location (distribution over the scalp), and latency of electrical "bumps" in surface ERP recordings. In both cases, there are problems of definition (what is a bump?) and measurement (how do we assign numerical values to the magnitude of a bump uncontaminated by the influences of other bumps?). Whereas the phrenologists had little outside help on these difficult problems, we have the theoretical and practical aid of electrical field theory, as discussed in the bulk of this chapter.

The second, and deeper, parallel is the attempt to investigate human psychological processes and their neural substrates by measuring physical variables related to the brain (skull bumps in one case, electrical bumps in the other) thought to map onto those processes. The psychological constructs used by phrenologists and ERP researchers are very different, but the attempted mapping between physical variables and psychological constructs is similar nonetheless. Phrenologists related their dependent variables to mental faculties such as "acquisitiveness," "self-esteem," and "philoprogenitiveness." ERP researchers, in contrast, typically rely upon the constructs of modern cognitive psychology (e.g., "pattern recognition" and "stimulus classification"—Ritter, Simson, Vaughan, & Macht, 1982; "detection" and "recognition"—Parasuraman & Beatty, 1980; "phonetic processes"—Wood, 1975; "selective attention"—Picton, Campbell, Baribeau, & Proulx, 1978; "stimulus evaluation"—McCarthy & Donchin, 1981). To the extent that these information-processing constructs are more likely to stand the test of time than did the "mental faculties" of the phrenologists, we will have the advantage that one end of the mapping we seek to determine is better established. However, if the constructs in fashion today are found wanting and are replaced, then any mapping relationship involving such constructs is correspondingly weakened (cf. Von Eckardt Klein, 1978).

Assuming that we have been lucky enough to choose valid psychological constructs, an important remaining problem is the nature of the mapping that we assume to exist between psychological processes and surface ERPs. We often conclude that a given ERP component "reflects," "manifests," or "indexes" a given psychological process (e.g., "The results support the hypothesis that NA and N2 reflect sequential stages of information processing, namely, pattern recognition and stimulus classification"—Ritter *et al.*, 1982, p. 909). It is difficult to determine from the literature just how strongly the terms "reflect," "manifest," and "index" are meant to be taken. In their strongest sense, such terms imply the same one-to-one relationship between surface ERPs and information-processing concepts that the phrenologists assumed to exist between bumps on the head and mental faculties.[1]

Having concluded that "ERP measure X reflects psychological process Y," based on experiments in which manipulations thought to influence process Y produce systematic effects on measure X, it seems to be only a small and natural step to conclude that ERP measure X can now be used as a measure of process Y. But note that such a suggestion involves a subtle but crucial logical shift: From the empirical fact that experimental manipulations thought to influence process Y produce systematic effects on ERP measure X, we do not know *what proportion* of the neural events that mediate psychological process Y in fact contribute to ERP measure X. That proportion could be high, in which case the ERP measure would have considerable value to psychologists as an indicator of properties of the process—for example, its onset, duration, and offset, and its presence or absence and relative magnitude across experimental conditions. However, the same experimental effects could be obtained if the proportion of the neural events relevant to process Y that also contribute to ERP measure X were extremely small. In the latter case, one could be misled by drawing conclusions about the time course or other aspects of the process, because only a small part of the relevant neural events will be observed.

For the reasons discussed in the preceding section—in particular, the aggregate, incomplete, and biased character of surface ERPs—we believe it to be unlikely that more than a relatively small proportion of the neural events that mediate a given psychological process are evident in surface ERPs. We would be delighted, of course, to be proved wrong in this assumption. The problem, however, is that deciding the issue requires knowledge of the mapping between the psychological process in question and the neural events that mediate it, as well as the mapping between those neural events and the surface ERPs said to reflect those processes. That is, it presumes exactly the knowledge that psychophysiological ERP research and other approaches to investigating the neural substrates of mental processes seek to obtain.

In the absence of such information, what type of relationship should we assume to exist between surface ERPs and psychological processes? In other words, how can we relax the excessively strong one-to-one assumption analogous to the one made by Gall, while still attempting to establish relationships between ERPs and psychological processes that have empirical and theoretical value? We have no compelling answers to these questions, merely some biases and hunches. Because it seems unlikely that we will ever know exactly what proportion of the neural events that contribute to a given psychological process are recordable in surface potentials, we believe it prudent to adopt a stance of explicit agnosticism on that issue and to avoid making empirical or theoretical decisions whose validity heavily depends on it. Having adopted such a stance, what contributions to the understanding of psychological processes and their neural substrates can psychophysiological ERP research make? In our opinion, there are three.

The first contribution requires determination of the anatomical structures and neurophysiological pro-

[1] *Editors' Footnote:* While the authors' critique of the "strong mapping" view may be quite cogent, the view is only one of a number of approaches to the inclusion of psychophysiological tools in the psychologist's armamentarium. For alternative, more positive views see chapters in the Processes and Applications sections of this book (especially, 11, 12, 23 and 26).

cesses that generate the surface ERPs of interest. As noted in the preceding section, that is a difficult but not an intractable problem. Based on such information, modern bumpologists would then be in a position to conduct experiments capable of suggesting that "structure X is involved in psychological process Y," even though such experiments could not establish either the relative magnitude of structure X's contribution or the information-processing operations performed by structure X as its contribution to process Y. Nevertheless, at this stage of the game, even the limited information provided by such experiments would be valuable, both in its own right and in establishing an empirical link to animal experiments in which more extensive neurophysiological investigations can be performed.

The second contribution concerns the use of ERPs as purely psychological tools without attempting to relate psychological processes to the brain. This use of ERPs involves a program of experiments designed to determine the mapping between psychological processes and ERPs, no matter how complex that mapping may be. Such a program would explicitly acknowledge the improbability that any psychological process will map in a one-to-one manner onto a given ERP measure, as well as the possibility that only a small proportion of the neural events relevant to a particular process may be evident in surface ERPs. It should be clear that the likelihood of success of such a program is inversely proportional to the complexity of the mapping. The success of such a program also depends upon solving an important ERP identification and measurement problem. In order to study the effects of different experimental conditions on a particular ERP component, we must be able to identify that component unambiguously in the different conditions. However, because of the principle of superposition and because of the broad time course and scalp distribution of many ERP components, what appears to be the "same" ERP phenomenon in different conditions on morphological grounds (e.g., a broad positivity between 300 and 600 msec, largest at the parietal midline), may not be generated by the same neural events.

The third type of contribution involves the use of ERP measures to discover patterns of organization in the CNS not evident in, or not yet discovered with, other experimental techniques. For example, Regan and Beverley (1973) used ERPs to suggest the existence of a class of cells in the visual system sensitive to direction of motion toward and away from the observer. Once its existence was known, this phenomenon was studied further using psychophysical techniques, but it was originally discovered electrophysiologically.

In conclusion, we believe that the contributions of psychophysiological ERP research can be enhanced by considering explicitly the nature of mapping assumed to exist between surface ERPs and psychological processes. Empirical correlations between ERPs and experimental variables thought to be related to psychological processes have been and will continue to be reported. What requires careful consideration is what such correlations imply. We modern bumpologists would be wise to cultivate Gall's mental faculties 10 and 17 ("cautiousness" and "hope").

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