NAVAL RESEARCH

REVIEWS

407-C

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PROFILES IN SCIENCE

Professor Jersey Neyman

Professor Jersey Neyman, who is Professor and Director of the Statistical Laboratory, University of Caiifornia, Berkeley since 1938, is one of the worlds's foremost statisticians. Dr. Mina Rees persuaded Professor Neyman to join the ONR program at its inception in 1946, and he has remained a contractor to the present. He has worked primarily with ONR's Mathematics and Meteorology Programs. Professor Neyman is considered a pioneer in the fundamental theory of estimation and testing statistical hypothesis. As attested to by his many publications he has successfully applied his methods to research in the fields of set theory, probability, statitics, astronomy, biology, behavioral science, and weather modification. He has received five honoary doctorates, is a member of the National Academy of Science, and was awarded the U.S. National Medal of Science.

Magnetic Fields of the Human Brain

S. J. Williamson, L. Kaufman, and D. Brenner*

University of New York

The purpose of this research supported by the Office of Naval Research is to better understand the two hemispheres of the brain, how they function and interact. The Navy is interested in this work as a way to increase the effectiveness of Navy personnel by (1) improving screening and selection procedures and (2) developing means of enhancing individual performance.

A major working hypothesis of applied psychobiology is that paper-and-pencil tests measure primarily left-brain functions but do not provide a useful index of the right-brain. From this hypothesis it follows that optimal assignments cannot be achieved until a way is found to measure the effectiveness of an individual's right hemisphere. It is anticipated that the use of neurological testing as a substitute or a supplement to paper-and-pencil aptitude testing may enable the Navy to identify those people who can function well in situations of stress and imminent danger. Another selection problem that merits investigation is how monotonous jobs affect performance. It is quite possible that information gained from such testing could provide a better understanding of neurological relationships and lead to improved stimulus presentations for naval equipment displays and training devices. Also the techniques developed through this research may have clinical applications in the study of brain abnormalities.

Introduction

There is a fundamental law of physics that movement of electrical charge produces a magnetic field in the surrounding space. First enunciated in the early 19th Century, this law bears the name of its discoverers: the French scientists Biot and Savart. Electrical currents are known to flow within the human body. By the Biot-Savart law these currents must be accompanied by magnetic fields. The early studies in the 1960's of biomagnetic phenomena dealt with relatively strong fields generated by organs such as the human heart. Because of their relative weakness, fields associated with current flow in the human brain were much more difficult to measure. With the advent in the past decade of

*Dr. Williamson is Professor of Physics at New York University. He is well known for his many publications in the fields of polarmetry, anti-ferromagnetic resonance, superconductivity, ultra low temperature physics, and air pollution. He is a member of the National Academy of Science. Dr. Kaufman is Professor of Psychology at New York University. His field of research is visual perception and its electrophysiological basis. Dr. Brenner a Post-Doctorial Fellow at New York University.

ultra-sensitive magnetic field detectors it has become possible to detect the weakest of biomagnetic phenomena. An entire field of study, now known as Biomagnetism [1] has come into being. The list of organs that are now known to produce detectable magnetic fields continues to grow (Figure 1).

Biomagnetic fields produced by the various organs of the body range in strength over four orders of magnitude, with 5 picotesla (in the *Systeme Internationale* units) representing the midpoint on a logarithmic scale. All of these fields are minute in comparison with the earth's steady field of about 50 microtesla.

The strongest biomagnetic field is produced by magnetic contaminants accumulated in the lungs of workers in certain occupations, such as asbestos miners and arc welders. Also comparatively strong are magnetic fields generated by polarization currents which flow in heart muscle during the cardiac cycle (magnetocardiogram) or in skeletal muscle when flexed (magnetomyogram). Signals from the heart of a fetus after about the twentieth week of gestation have also been measured (the fetal magnetocardiogram). Associated with the eye is a steady field set up by currents responding to the battery action which maintains a difference in potential of about 100 mV between cornea and retina (magnetooculogram). The weakest fields yet detected are associated with neural activity in the human.

Neuromagnetism

Physiologists have longed for a technique that directly monitors neural processes at a distance. In a limited sense, magnetic field studies fulfill this desire. Neuromagnetism, the detection and study of these fields, is now passing out of the initial exploratory stage and is beginning to make significant contributions to our understanding of brain function. Two classes of neuromagnetic field exist. One is generated by the spontaneous electrical activity of the brain, whose best-known example is the "alpha-rhythm," while the second is produced by electrical activity resulting from stimulation of sense organs. The stimulus-evoked fields have counterparts in the conventionally measured variations in electrical potential which are indirectly established on the scalp by the neural currents inside the skull. Thus an alpha rhythm may be found in recordings of magnetic activity called the magnetoencephalogram (MEG) and also in its counterpart, the classic electroencephalogram (EEG). The counterpart of the evoked field is the evoked potential.

Although both scalp potentials and magnetic field ultimately have neural currents as their source, measurements of the field can yield information about brain function that differs from that obtained from potential measurements. This might be anticipated according to the Biot-Savart law because a detected field arises from the strong neural

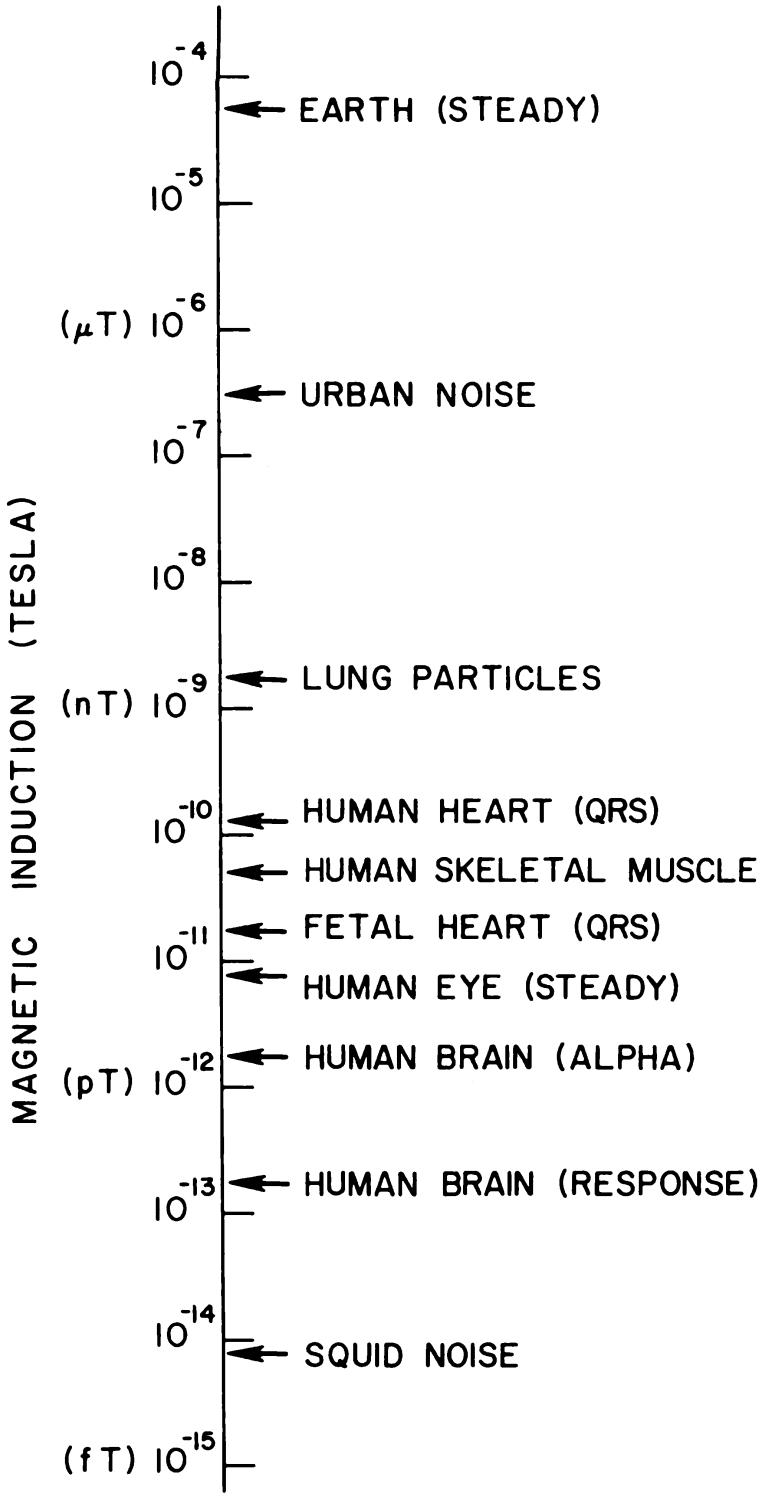

Figure 1 – Magnetic fields of the human body are much weaker than typical environmental magnetic noise at low frequencies. A modern field detection system has more than adequate sensitivity indicated by the entry "SQUID noise" for measurements of many biomagnetic fields.

currents close to the scalp; whereas skin voltages are associated with weaker currents in the dermis, a result of signals propagating outward from the brain and through the skull. Thus magnetic fields may well be a direct indication of brain activity, which voltages are not. Support for this point of view comes from recent experimental results that show that the evoked field is strongly localized over the active region of the brain, whereas the evoked potential is more diffuse, often appearing anywhere on the scalp. One implication is that when an evoked response is due to more than one set of active neurons at differing locations, it will be difficult if not impossible to distinguish the activity of each set by voltage measurements, whereas this may be achieved with field measurements.

Field Monitoring Techniques

The first detection of a biomagnetic field—that from the heart—was accomplished in 1963 by Gerhart Baule and Richard McFee [2] using a coil of two million turns of wire with ferrite core placed near the chest. They detected a voltage across the coil induced by the time-rate of change of the cardiac field. Better sensitivity and dc response is now obtained from a sensor based on the superconducting quantum interference device (SQUID) [3]. Having dimensions of only a centimeter or so, this device relies on the wave-like properties of electrons in metals when cooled to a temperature where they exhibit superconductivity. With modern radio frequency technqiues to monitor the response of the SQUID when it senses a magnetic field, remarkably high sensitivity has been achieved [4].

While the SQUID itself can detect magnetic fields of interest, it is often more convenient to couple fields to it by means of a "flux transporter." This is a closed loop of superconducting wire which is wound to form a "primary" coil at the location of the field of interest and a "secondary" coil near the SQUID. A magnetic field at the primary coil causes shielding currents to flow in the flux transporter. As the current flows through the secondary coil it establishes a magnetic field at the SQUID. One advantage of remote sensing by a flux transporter is simply that the primary can be wound in any of several configurations to reduce background noise. A single loop (Figure 2a) senses the total magnetic field passing through it, averaged over its area, and provides no particular advantage. Two identical loops (Figure 2b) wound in opposite directions renders the primary insensitive to uniform field, since a positive signal produced in one is cancelled by a negative in the other. This is called gradiometer, since it responds to the gradient, or rate of increase of field with position, along the axis. A further elaboration with two gradiometers mounted back-to-back (Figure 2d) is insensitive to both uniform fields and uniform field gradients. An example of such an arrangement, known as a second derivative gradiometer, is shown in Figure 3.

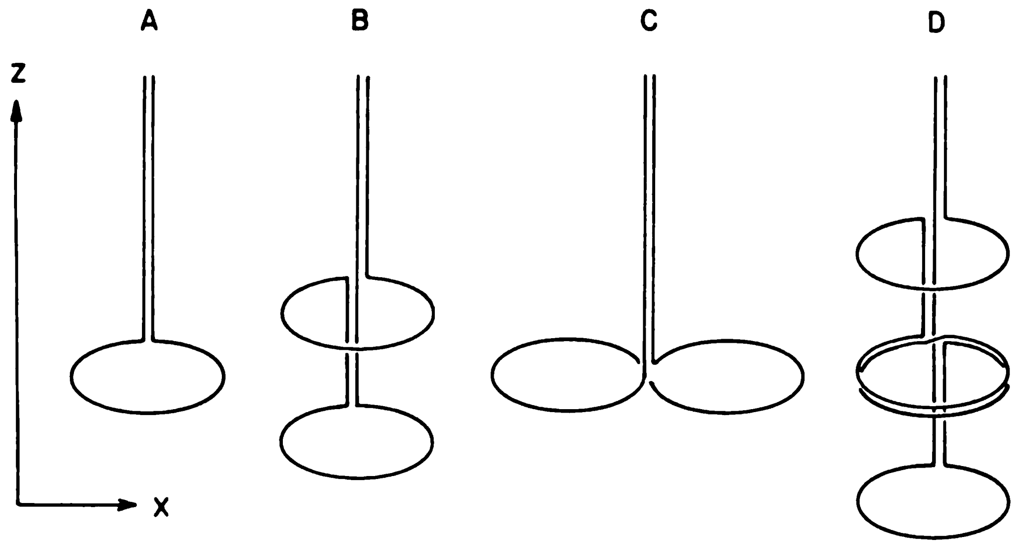

Figure 2 – Various configurations for the primary of a flux transporter: A. magnetometer, B. gradiometer, C. off-diagonal gradiometer, and D. second derivative gradiometer.

A major challenge in neuromagnetic measurements is detecting signals of interest in the presence of background field variations that may be over a million times stronger. One solution is magnetic shielding, whereby sheets of high permeability material forming the surfaces of a room intercept external magnetic fields and leave the interior relatively field-free. The most effective room was designed and constructed at the Francis Bitter National Magnet Laboratory at M.I.T. by David Cohen, with partial support from the Office of Naval Research (Figure 4). The noise level inside is lower than the inherent noise in the SQUID detector itself. Many of the biomagnetic fields listed in Figure 1 were discovered by Cohen and his collaborators inside this room [5].

Our own approach at New York University is based on our desire to avoid the cost and space limtations imposed by shielding. We take advantage of the fact that most background fields outdoors, in laboratories or in hospitals are relatively uniform in space. Therefore a gradiometer or second derivative gradiometer discriminates against them in favor of fields from a local source, such as the head, which may be positioned near the lowest coil of the gradiometer so that the field of the source, which diminished rapidly with distance, couples effectively to only that coil. The cover picture shows the arrangement which successfully monitors neuromagnetic fields in our laboratory, located on the ninth floor of a building in the center of Manhattan. Our noise level is a factor of 10 greater than the level of 10 femtotesla per root Hertz bandwidth obtained in the M.I.T. room in the spectral range 5 Hz to 8 kHz; and our noise increases approximately as f^{-1} below 5 Hz. Preliminary results incorporating active filtering techniques indicate that this noise level can be substantially improved.

Figure 3 – Supporting structure for a SQUID magnetic field detector displayed beside the cryogenic dewar in which it operates. The SQUID is inside the cylindrical shield located about one-third of the way up the 70 cm long supporting rod. At the bottom is the second derivative gradiometer sensing primary, shown in larger scale in the inset, consisting of niobium wire wound on a 2.4 cm diameter quartz form. (Photographs courtesty of S.H.E. Corporation, San Diego, California).

Figure 4 – Magnetically shielded room at the Francis Bitter National Magnet Laboratory at M.I.T.

Spontaneous Activity

The magnetic field generated by spontaneous activity of the brain was discovered in 1968 by David Cohen using an induction coil and signal averaging technique [6]. SQUID detectors now provide signals whose quality is comparable with that of the standard EEG (Figure 5). When the alpha rhythm is well developed, the field pattern is found to embrace the head as illustrated in Figure 6. Rather detailed studies

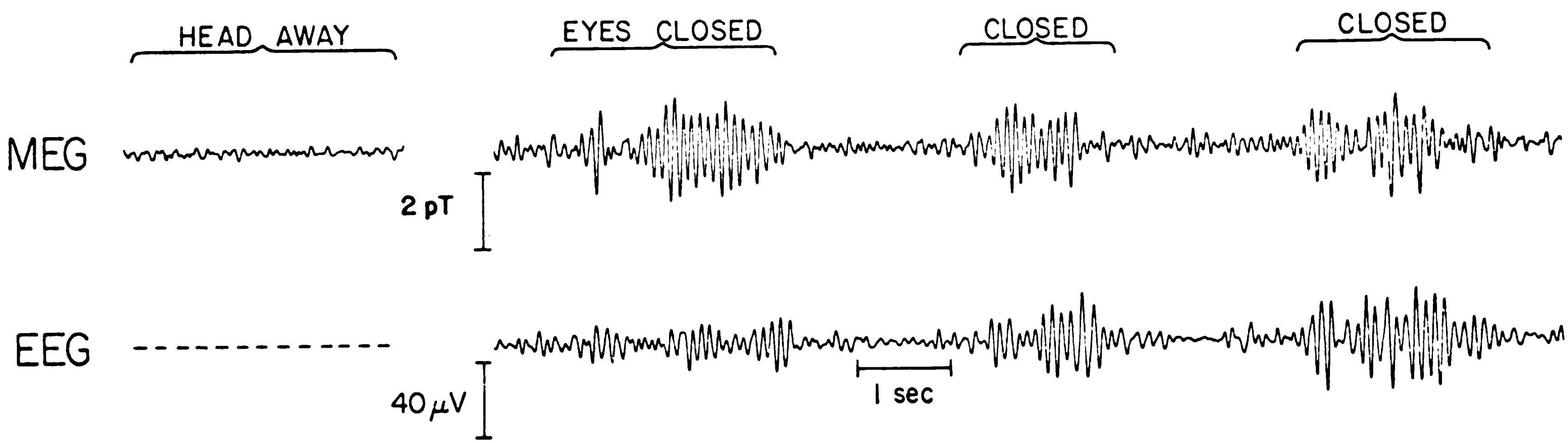

Figure 5 – Simultaneous magnetoencephalogram and bipolar electroencephalogram recordings for the frequency range of 4-15 Hz. From D. Cohen, Science, 175, 664 (1972).

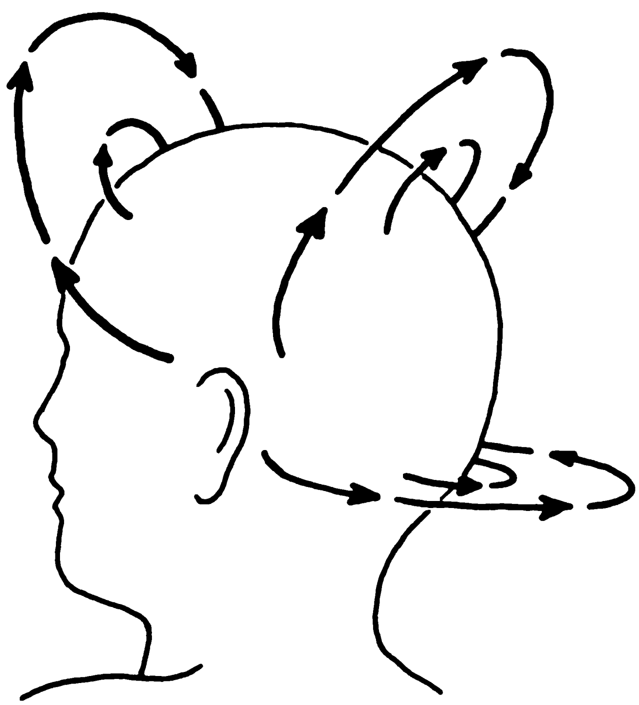

Figure 6 – Magnetic field pattern for oscillatory activity at the alpha frequency. During the subsequent half cycle the direction of the field reverses.

have been carried out on normal subjects [7,8], sleeping subjects (7) and epileptics [9]. By comparing magnetic field and voltage records, these studies indicate that a close but not complete association exists between generating sources for the two phenomena; the alpha rhythm in the EEG is correlated with that in the MEG in normal awake subjects, but this correlation disappears while the subject is asleep. A similar lack of correlation is found in epileptics. The sources for signals at frequencies other than the alpha frequencies appear either to be disassociated, or the currents are preferentially oriented so that their magnetic fields are largely parallel to the scalp and hence remained undetected in these experiments. So little information is available about magnetic field patterns that it is premature to speculate about the nature of the sources. These spontaneous signals from the brain remain intriguing and unexplained. Even the physiological source and function, if any, of alpha rhythm activity has not been firmly established.

Evoked Fields

We believe that more enlightening studies of brain function can be carried out with the well-known technique of evoking a response by

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employing stimuli, such as visual, tactual or auditory stimulus. One then knows where the initial brain activity takes place, i.e., the primary projection area of the brain. In such studies, signal averaging techniques must be used for both potential and field measurements to bring the relatively weak evoked response above the level of the spontaneous activity and background noise. Either transient or steady state response can be measured. The former is the response to an isolated stimulus, separated in time from other stimuli so that the response to one stimulus ends before the next stimulus is presented. The steady state response is obtained when stimuli are presented in rapid succession at a constant rate. The transient and steady state techniques would yield identical information if the brain were a linear system, but this is not to be expected. The transient neuromagnetic response to a visual stimulus consisting of a brief flash from a strobe light is illustrated in Figure 7. The peaks and troughs which are similar to the shape of the evoked potential are thought to represent different stages of information processing. By contrast, the steady state response is analyzed

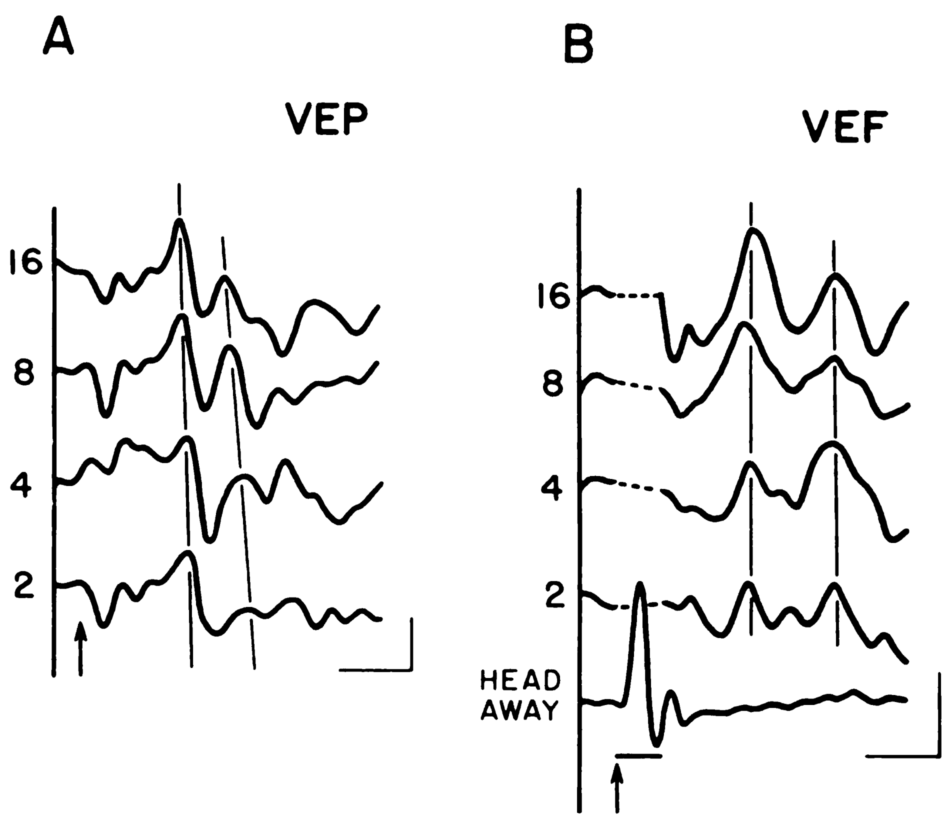

Figure 7 – Visually evoked potential and visually evoked field averaged over 100 responses for each of four levels of flash intensity. A 225 ms duration of response is illustrated. The "heat away" trace shows a magnetic artifact that accompanies the flash of the lamp. From T.J. Teyler, B.N. Cuffin and D. Cohen, Life Sciences 15, 683 (1975).

in terms of its harmonic content; and studies using stimuli at various frequencies may reveal the effect of specialized neural channels which play dominant roles in different frequency regions.

Visually Evoked Field

Teyler, Cuffin and Cohen at M.I.T. have studied the transient evoked field found near the back of the head for light flashes of varying brightness [10]. At least one significant difference between the visually evoked field (VEF) and visually evoked potential (VEP) was reported: as the flash is made brighter the response amplitude of the VEF continues to increase, but the amplitude of the VEP tends to level off. There is also some evidence that the peaks of the VEP occur sooner with increasing brightness but not the peaks of the VEF (Figure 7). Unfortunately the significance of these findings is not yet clear, and no correspondence has been established between the neuromagnetic activity and the physiology of the brain.

The work at our Neuromagnetism Laboratory at N.Y.U. has dealt exclusively with the steady state response and has revealed new features of the nature of brain function. An oscilloscope provides the light stimulus which consists of vertical parallel bars on a dark field. This pattern is called a sine wave grating, because the luminance varies sinusoidally across the screen. It is characterized by its spatial frequency, the number of cycles which are seen within one degree of visual angle (Figure 8a). Its use is inspired by the contemporary notion in psychology that at least for simple patterns the visual system responds to the pattern's spatial frequency content (in this sense, the visual system takes the Fourier transform of the scene). Temporal modulation of the pattern, so that it would be repetitively presented for purposes of signal averaging, is accomplished by moving it back and forth by half a spatial wavelength, thereby reversing the contrast at the selected rate (Figure 8b), or by alternating between the grating and a blank field having the same average luminance. We are then sure that the response of the subject is to a change in pattern, not a change in overall brightness of the screen. The two modulation sequences give essentially identical responses.

The first remarkable result is that the VEF is sharply localized near the back of the head over the visual cortex—the vision center of the brain [11]. Measurements at various positions up the midline reveal an appreciable field variation only over a distance of about 5 cm, as shown in Figure 9. A response can also be observed over a span of approximately 10 cm to either side of the midline. The VEP by comparison is considerably more widespread, being strong even at the vertex at the top of the head. The second noteworthy aspect is that along the midline the VEF has a unique phase, whereas the VEP does not. Phase denotes where within the temporal cycle of the stimulus the

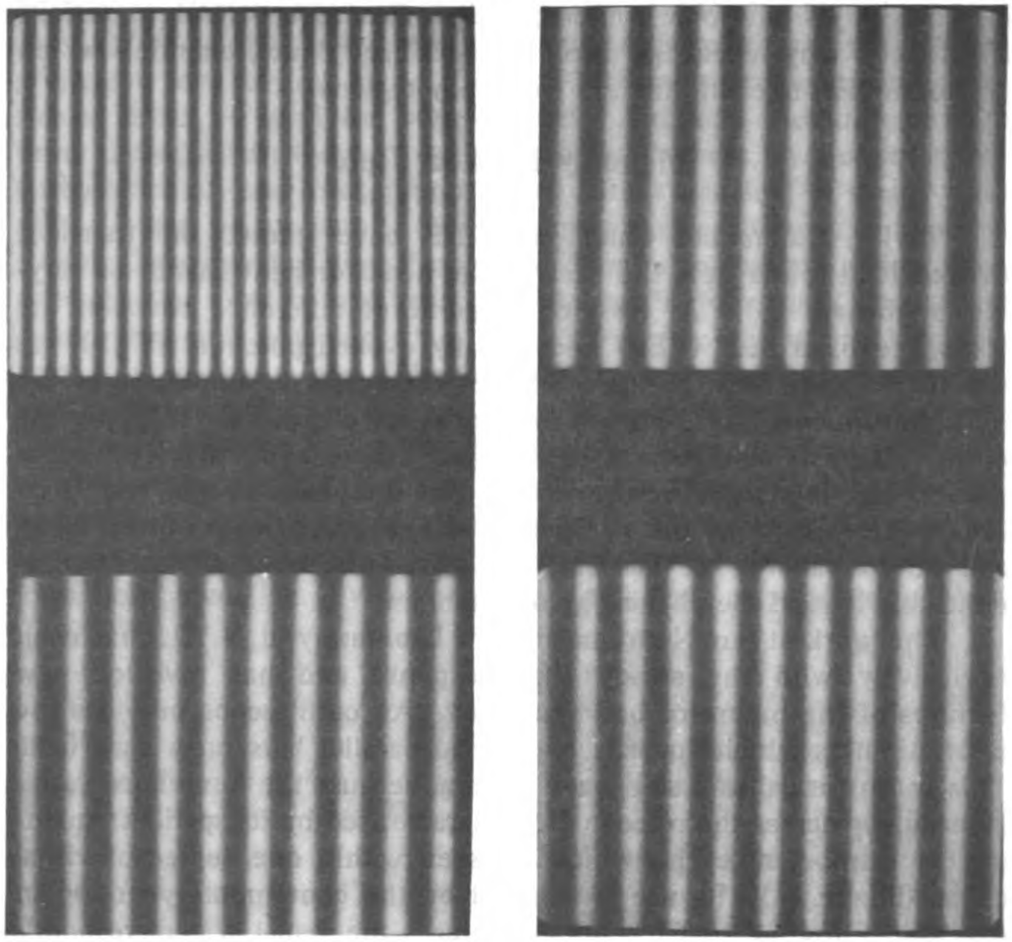

Figure 8 – (a) Patterns illustrating sine wave gratings of differing spatial frequency, the upper being twice that of the lower; (b) contrast reversal sequence in which a grating is shifted laterally by half a spatial wavelength.

response produces its peak effect (maximum field directed outward from the scalp or maximum positive voltage with respect to a reference electrode on the right earlobe). The reason for the variation in phase of the VEP up the midline is not known, but the effect may result from the addition of signals propagating from at least two different active centers of the brain. The uniqueness of the phase of the VEF provided an opportunity for us to determine how it varies with the temporal rate at which the pattern is changed. We found that the phase increases in proportion to temporal frequency. This led us to conclude that the peak magnetic field is produced a fixed time after the stimulus is presented, regardless of how rapidly it is presented. We call this time delay the "latency" of the response. It is a characteristic feature of the human visual system.

A particularly interesting finding was that the latency of the subject's response increases with the spatial frequency of the stimulus. The effect illustrated in Figure 10 is quite dramatic, with latency increasing from about 90 ms for low spatial frequency to 250 ms for high.

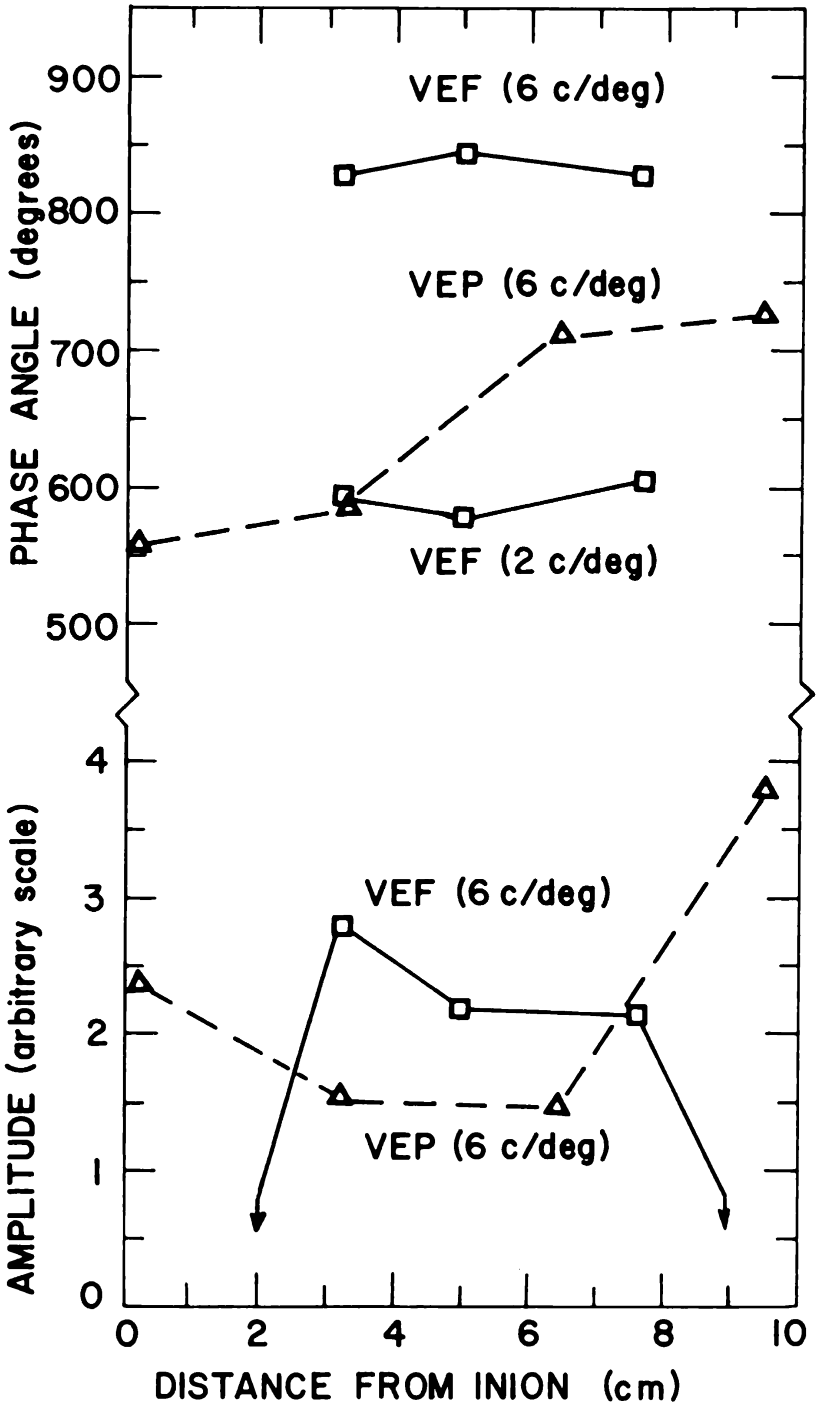

Figure 9 – The visually evoked field has an appreciable amplitude only near the visual coretx of the brain between 3 and 8 cm above the inion. The inion, which is the bump found near the base of the skull, serves as a benchmark. The stimulus pattern is specified by its spatial frequency in cycles per degree of visual angle (c/deg). The visually evoked potential extends over a much broader region, even appearing at the vertex at the top of the head. Variation of temporal phase with position is also more pronounced. Values of phase lying between 360° and 720° imply that the response has dropped behind the stimulus by one cycle.

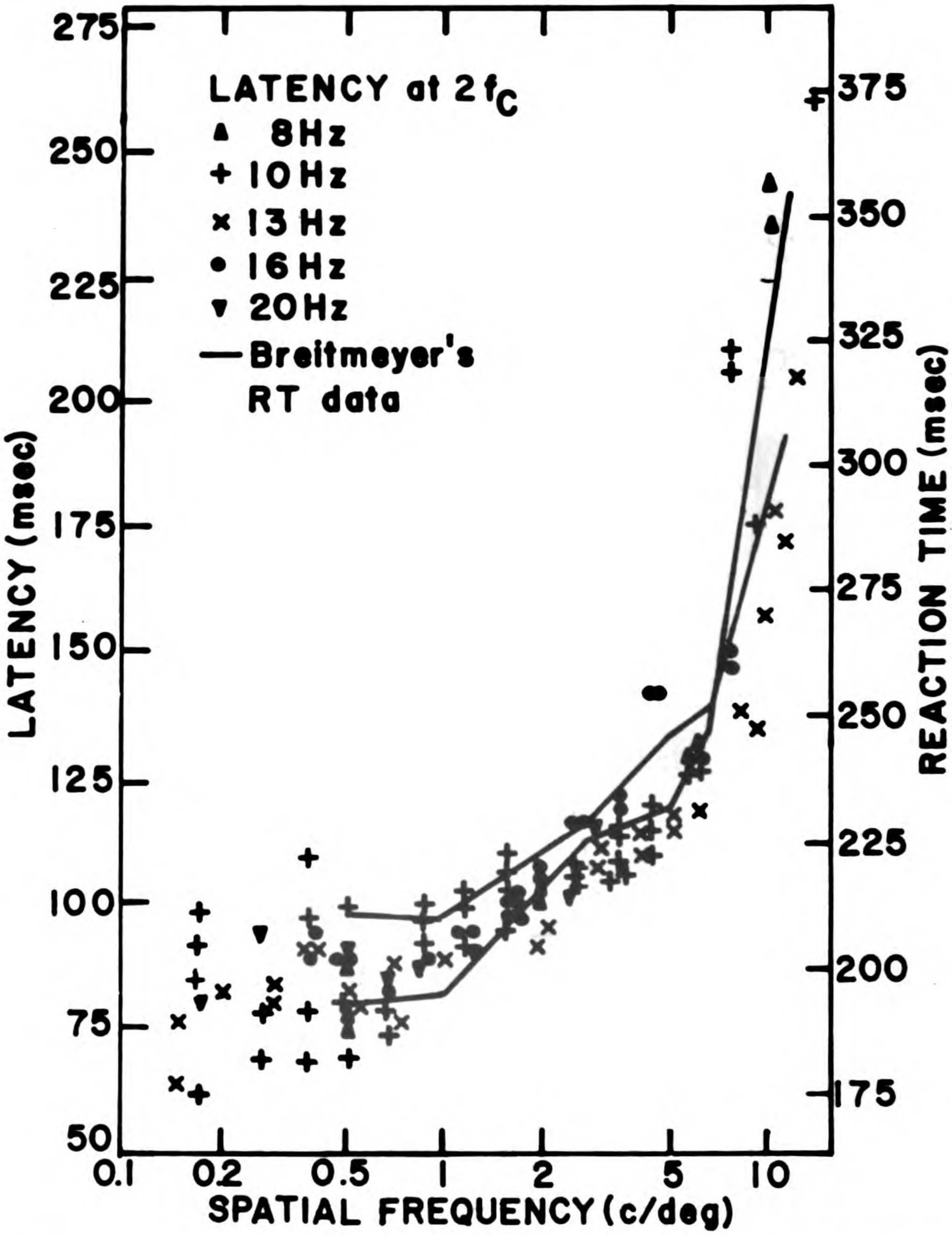

Figure 10 – Latency of the magnetic response (left axis) is deduced from data at a number of stimulus frequencies indicated in the legend. The variation with spatial frequency of the stimulus pattern is identical with that observed in reaction time measurements by B. Breitmeyer as indicated by the solid lines (and right axis).

The independence of latency from spatial frequency at the low end of the curve and sharp rise at the high correlate with characteristics of suspected specialized channels in the visual system, but it would not be appropriate to go into these details here. Of more relevance is the fact that there is a direct correlation between latency, which is a measure of neural activity, and a subject's simple reaction time, which is a measure of human performance. Also shown in Figure 10 are results reported by Bruno Breitmeyer who showed that the reaction time of an observer to a briefly presented grating also increases with spatial frequency [12]. Our own reaction time experiments confirm his finding that it takes considerably longer to respond when the pattern has high spatial frequency than low. Figure 10 shows that the variation in reaction time is predicted from the neuromagnetic latency simply by adding a constant interval of about 115 ms. This interval we identify as the motor response time; and it evidently is independent of pattern features. Our neuromagnetic data suggest that there is a serial arrangement of visual and motor responses. This conclusion is supported by experiments with quite different stimuli.

Somatically Evoked Field

Electrical stimulation of various areas of the body provides a good teat of the accuracy with which neuromagnetic techniques can locate active sets of neurons within the somatic cortex. Direct stimulation of the cortex during brain surgery, with portions of the skull removed, has previously revealed the locations of primary activity related to somatic sensation [13]. Areas of the body map onto corresponding regions of the cortex on the contralateral side of the head, just posterior to an indentation of the cortex known as the Rolandic fissure (Figure 11). This ordering of projection areas is called the sensory homunculus. We have discovered a somatically evoked field by applying a mild, repetitive, electrical stimulus to the little finger or the right hand and monitoring changes in the magnetic field which is normal to the left hemisphere [14]. Figure 11 schematically illustrates the pattern of evoked field at an instant when the field has its maximum strength. One half cycle later the field pattern has reversed its direction.

The center of the pattern can be located with an accuracy of about 1 cm and lies close to the appropriate position of the homunculus. When the thumb is stimulated instead, the pattern shifts downward along the Rolandic fissure by about 2 cm, again as expected from the homunculus. Such localization has not heretofore been achieved by conventional measurements of voltages between various positions on the scalp. Details of the observed magnetic field pattern are similar to what is expected from a source that resembles a current dipole. This is a localized current flowing in a straight line between two nearby points

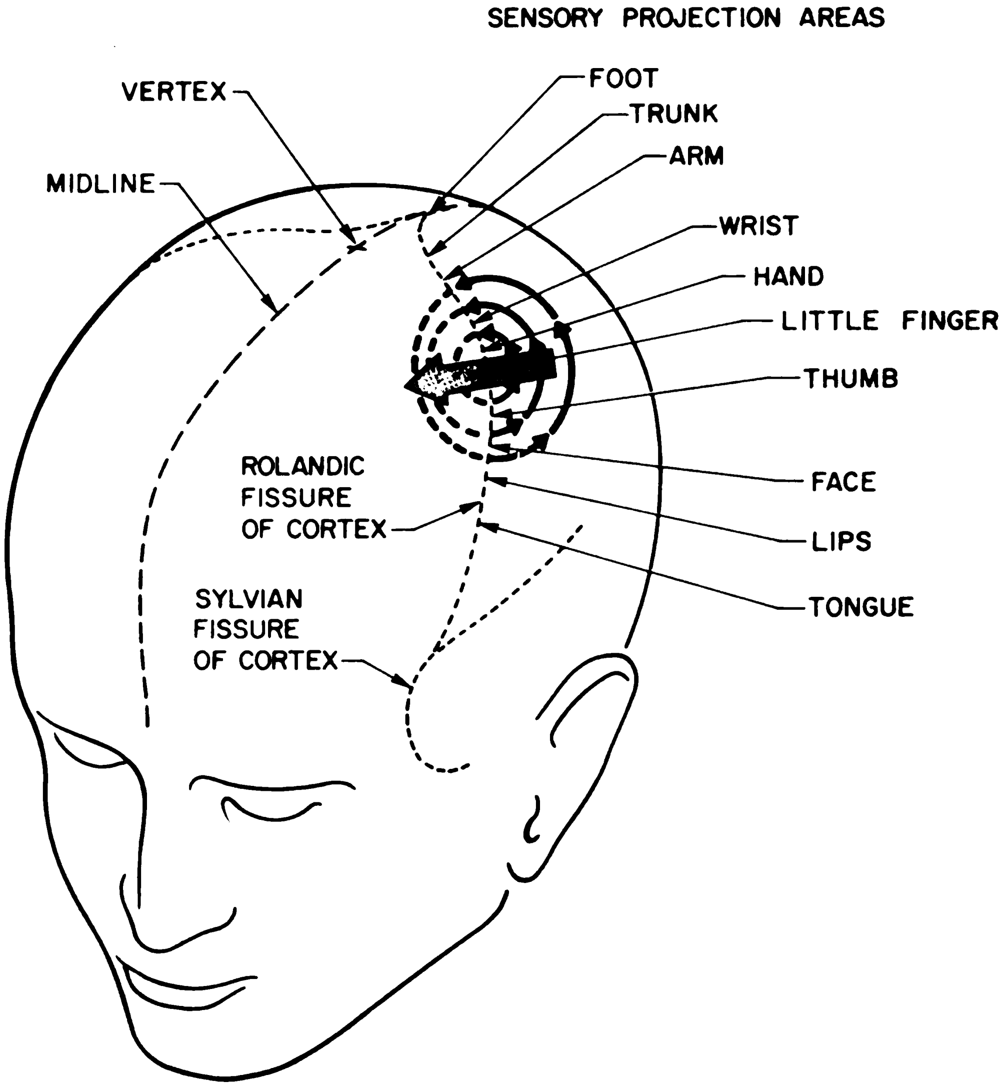

Figure 11 – Projection areas ranging along the Rolandic fissure in the brain believed to respond to somatic stimuli applied to various areas of the body. The observed magnetic field pattern for stimulation of the little finger is illustrated at a moment of maximum response. The broad arrow shows the direction of electrical current that would account for the field pattern.

in response to biological activity. The presence of a current dipole causes a backflow of current through the surrounding medium. The observed field pattern indicates that the current dipole is aligned perpendicular to the Rolandic fissure. Thus, to a good approximation the neuromagnetic field can be ascribed to the movement of electrical charge in the cortex toward and away from the fissure. As yet we are unaware of any theory for large scale activity of the brain that accounts for this conjecture.

The phase of the somatically evoked response also increases with stimulus frequency, as we observed for the visually evoked response.

At low frequencies there is some inter-subject variability among four subjects studied, but above 18 Hz all exhibit a common trend which can be characterized by a latency of 70 ms. We have completed reaction time measurements as well and obtained an average value of 172 ms for the same subjects. These values indicate that the motor response time adds 102 ms to the latency in order to account for the overall reaction time. This value is comparable to the value of 115 ms mentioned earlier for the motor response time as obtained from the visually evoked response. The agreement lends support to our serial processing model.

These studies of the evoked neuromagnetic fields support our contention that they provide a direct measure of activity in the primary projection areas of the cortex. The peak field appears as the culminating effect of prior signal processing at the cortical and lower levels and is prior to the initiation of motor responses. These results hold out the promise that we have hit upon a method for revealing the functioning of the brain at a level that is intermediate between recordings from gross scalp electrodes and microelectrode studies of individual neurons.

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"T-3 Again on the Move"

Fletcher's Ice Island T-3 was first sighted on aircraft radar in June 1950, and first occupied by Joseph Fletcher and Burt Crary in March 1952. It then became the base for weather observations and a variety of research projects sponsored by the Office of Naval Research during more than 20 years of drift around the Beaufort Sea. The station has been deactivated several times when the island became stationary, the most recent of which was in early fall of 1974 near the coast of Ellesmere Island, not far from the probable point where drift of the island began more than 25 years earlier.

Assisted by Arctic Ice Dynamic Joint Experiment (AIDJEX), the Naval Arctic Research Laboratory parachuted an ADRAMS (air-droppable RAMS) buoy on to T-3 in May 1976 at 82.2N 94.7W to monitor the movement of the island by tracking through a National Aeronautic and Space Administration (NASA) satellite, Numbus VI. Little movement was detected during the normal life of the buoy, which quit reporting in September 1976. No further sightings have been reported, and an attempt to relocate the island in the spring of 1977 near the last reported position was unsuccessful.

In early July 1977 the buoy unexpectedly produced several days of reliable position fixes through Nimbus VI, perhaps due to some consequence of warmer summer temperatures. The island had moved about 300 kilometers to the south and west (80.5 N 109.5 W) and seems likely to have resumed its steady drift around the Beaufort Sea. Surprisingly, the ice island is clearly visible in NOAA 5 images during the same period. Thus, two different satellite remote sensing tools confirm movement of the island which will lead to interest in the resumption of research at the station.

An Overview of Fault Tree Analysis

Richard E. Barlow*
University of California at Berkeley

The Navy has many complex operational systems in which accurate reliability evaluations may be crucial to mission accomplishment. Consequently, the Office of Naval Research is supporting research to develop improved methods for assessing the reliability of complex systems. One of the methods which appears to have good potential is fault tree analysis, an analytic procedure for providing an objective basis for analyzing system designs, justifying system changes, performing trade-off studies and demonstrating compliance with specified requirements. This type of analysis has been under development since the early 1960s. Recently, researchers have developed better fault tree methods, such as the improved qualitative and quantitative methods described in this paper. These methods, which were developed by Richard Barlow with the support of the Office of Naval Research, include (1) development of faster and more efficient algorithms for implementation in computer programs, (2) development of better decomposition methods associated with large fault trees and (3) implementation of fault tree analysis methods in diagnostic checking. The application of fault tree analysis methods has rapidly increased in many industries that employ systems whose failure would have serious economic and safety consequences. The aerospace, chemical and nuclear industries are prime examples. An actual application of fault tree analysis to a complex military weapon system has been made. The analysis was performed on a naval weapon system known as the close in weapons system.

Introduction

The Nuclear Reactor Safety Study [1] was sponsored by the U.S. Atomic Energy Commission and the U.S. Nuclear Regulatory Commission to estimate public risks from commercial nuclear power plants.

*Dr. Barlow is Professor of Industrial Engineering and Operations Research and Professor of Statistics and Director of the Operations Research Center at the University of California, Berkeley. His research has mainly been in the area of field reliability, theory and application. He was co-author with Frank Proschan of "Statistical Theory of Reliability and Life Testing."

This study has become the prototype for engineering risk investigations in many other areas besides nuclear safety. The principal analytic tool that was used in this study is Fault Tree Analysis.

The concept of Fault Tree Analysis was originated by Bell Telephone Laboratories in the early 60's as a technique with which to perform a safety evaluation of the Minuteman Launch Control System. Bell engineers discovered that the method used to describe the flow of "correct" logic in data processing equipment could also be used for analyzing the "false" logic which results from component failures. Further, such a format was ideally suited to the application of probability theory to determine the probability of critical fault modes. The Minuteman Safety Study was successfully completed using the new technique, and provided convincing arguments for the incorporation of a number oı equipment and procedure modifications [2].

This relatively new technique provides an objective basis for analyzing system designs, justifying system changes, performing trade-off studies and demonstrating compliance with safety requirements. The logic tree diagrams used in the approach make it a useful tool for both engineering and management, allowing visualization of the logic process involved. A recent conference volume surveys the state-of-the-art [3].

Fault Tree Construction

Fault tree analysis is a detailed deductive analysis that usually requires considerable system information. It is best applied during the design stages of a system. At that point, it can identify hazardous conditions and potential accidents in a system design and thus can help eliminate costly design changes and retrofits that would otherwise have to be made later in the system life cycle. Undesired events requiring fault tree analysis are identified either by inductive analysis or by intuition. These events are usually undesired system states that can occur as a result of subsystem functional faults. These events can be broad, all-encompassing events, such as "propulation system failure," or "friction brakes lock," or they can be specific events, such as "printed circuit board failure," or "hydraulic power unit failure."

The goal of fault tree construction is to model the system conditions that can cause the undesired event. Before the construction of the fault tree can proceed, the analyst must acquire a thorough understanding of the system. In fact, a system description should be part of the analysis. The analyst must carefully define the top undesired event. Practical considerations require that he scope the analysis, setting spatial and temporal bounds on the system. To make his analysis understandable to others, the analyst should clearly show all the assumptions made in the construction of the fault tree.

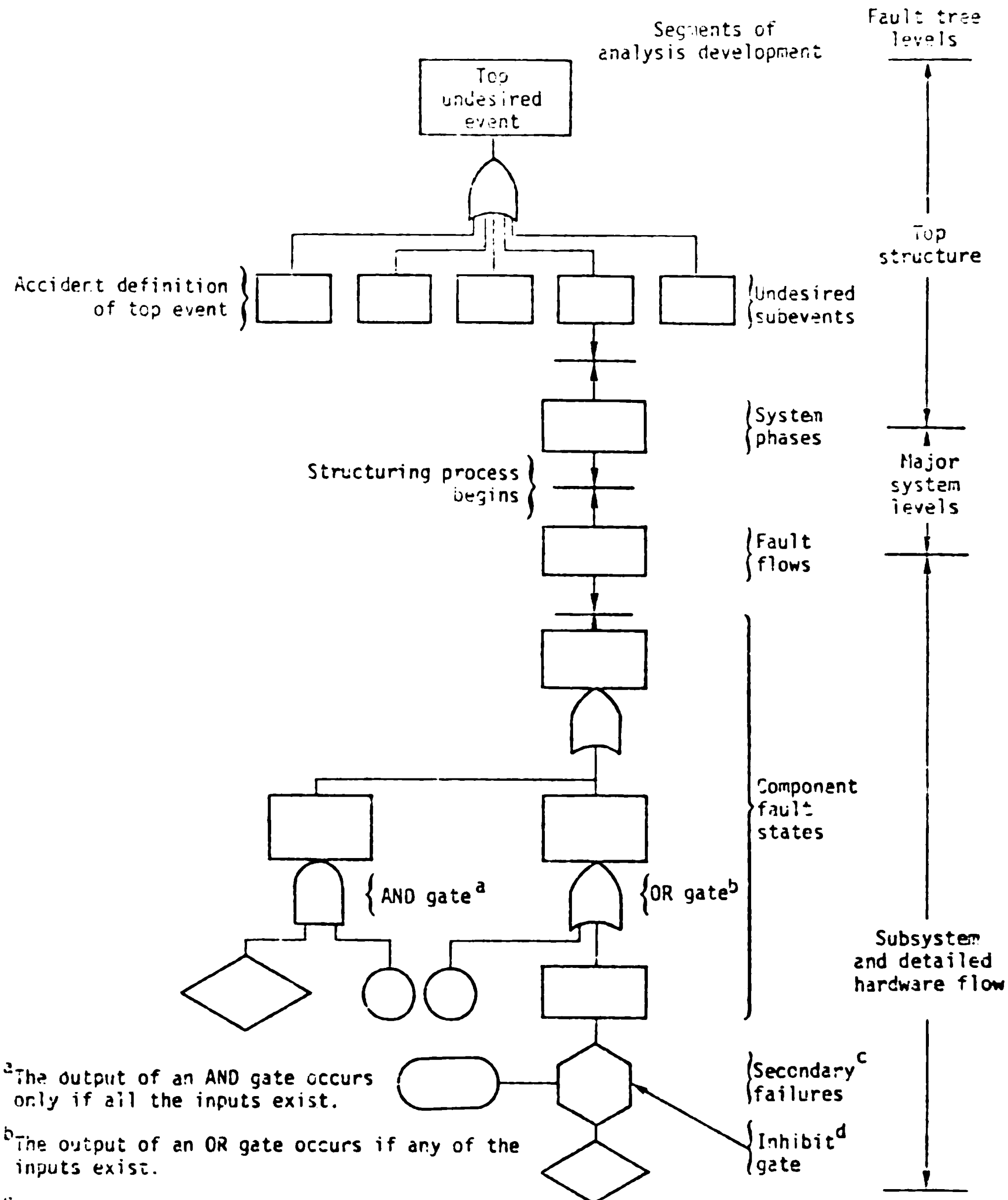
A fault tree is a model that graphically and logically represents the various combinations of possible events, both fault and normal, occurring in a system that lead to the top undesired event. The term "event" denotes a dynamic change of state that occurs to a system element.* For convenience, define two states for system elements, the OFF state (indicating the element is working properly) and the ON state (indicating either the element has failed or is operating inadvertently). The time at which the element is on is referred to as the fault duration time.

The fault tree is so structured that the undesired event appears as the top event in the fault tree (see Figure 1). The sequences of events that lead to the undesired event are shown below the top event and are logically linked to the undesired event by standard OR and AND gates. The input events to each logic gate that are also outputs of other logic gates at a lower level are shown as rectangles. These events are developed even further until the sequences of events lead to basic causes. The basic events appear as circles and diamonds on the bottom of the fault tree and represent the limit of resolution. The circle represents an internal or primary failure of a system element when exerised within the design envelop of the system. The diamond represents a failure, other than a primary failure, that is purposely not further developed.

A complete safety analysis on an extensive system such as a nuclear power plant or a chemical processing plant normally requires three levels of fault tree development, as shown in Figure 1. The upper level, called the top structure, includes the top undesired event and the sub-undesired events that are potential accidents and hazardous conditions that are immediate causes of the top event. The next level of the fault tree divides the operation of the system into phases, subphases, etc., until the system environment remains constant and the system characteristics do not change the fault environment. In this second level of fault tree development, the analyst examines system elements from a functional point of view. He uses a structuring process to develop fault flows within the system that deductively lead to a subsystem and detailed hardware flow, which is the third level of the fault tree. At the third level, the analyst is faced with one of the most difficult aspects of fault tree analysis. He must show if basic events are statistically independent. He then focuses his attention on common events that can simultaneously fail two or more system elements. The effects of any common environmental or operational stresses are studied, as well as the effects of the human factor in the testing, maintenance, and operation of the system.

Figure 2 is a relatively simple fault tree describing the logical sequences of events which can lead to rupture of a certain pressure tank.

*System elements include hardware, software, humans, and environmental factors.



[a]The output of an AND gate occurs only if all the inputs exist.

[b]The output of an OR gate occurs if any of the inputs exist.

[c]Out-of-tolerance failure of a system element — failure due to excessive operational or environmental stress.

[d]An inhibit gate is a special case of the AND gate. The oval indicates a conditional event

Figure 1 – Levels of fault tree development.

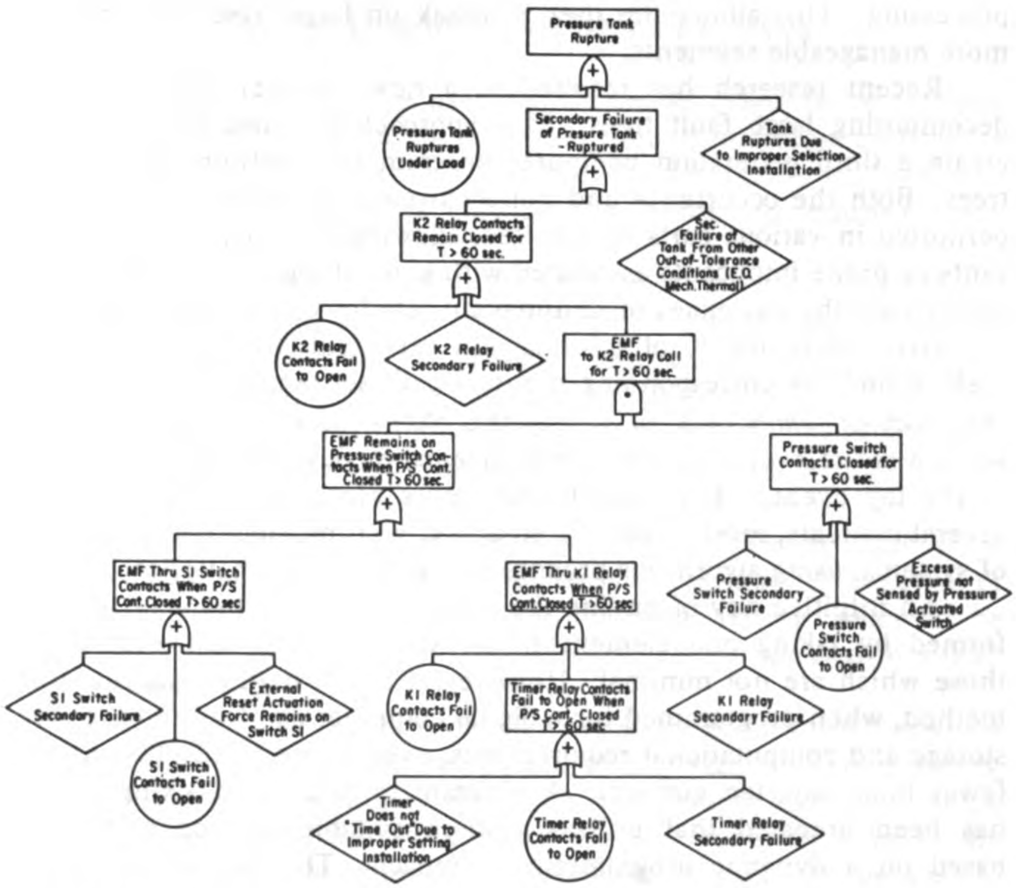


Figure 2 – Sequence of events which can lead to the rupture of a pressure tank.

A description of the system and additional discussion of fault tree techniques can be found in Barlow and Proschan [4].

Computerized Fault Tree Analysis

Much of the research activity in fault tree analysis has been directed toward the development of efficient algorithms for computer evaluation of fault trees. In particular, there now exist many computer programs for the determination of minimal cut sets [5]. A minimal cut set is a set of events whose occurrence causes the top event. This set of events cannot be reduced and still insure the occurrence of the top event. Using the minimal cut sets, a qualitative judgement can be made regarding the safety of the system and the identification of critical system elements.

A computer program, developed at the University of California, Berkeley, called MICSUP, uses an upward tree algorithm to calculate the minimal cut sets [6]. An important merit of the upward algorithm over its predecessor, MOCUS [cf. (5)], a downward method, is its ability to give the minimal cut sets of any intermediate gate without further processing. This allows the user to break up large trees into smaller, more manageable segments.

Recent research has resulted in a new "blocker algorithm" for decomposing large fault trees. This approach has also been used to create a third generation computer program for analyzing large fault trees. Both the occurrence and nonoccurrence of the same events are permitted in various parts of the tree, allowing the user to find implicants or prime implicants associated with general logic trees. Prime implicants are the analogues of minimal cut sets for general logic trees.

Given a family K of minimal cut sets, fault tree analysts often wish to find the corresponding minimal path set family, known also as the *blocking family* of K or simply the *blocker* of K. (A minimal path set is a set of events whose nonoccurrence ensures the nonoccurrence of the top event.) The need to determine blocking families arises in several contexts, most often in connection with modular decomposition of systems, using algorithms proposed by Billera and Chatterjee [7].

An intuitive way of finding the blocking family is to list all subsets formed by taking one element from each set in K and eliminating those which are not minimal. However, it is not hard to see that this method, when programmed for a digital computer can lead to excessive storage and computational requirements, even if the family K contains fewer than, say, ten cut sets. A program to find the blocking family has been prepared that utilizes a more suitable method essentially based on a dynamic programming approach. The cut sets are considered sequentially, and components in, say, the nth cut set which have not occurred in cut sets earlier in the sequence are used to augment a table of "partial" minimal path sets, that is, minimal component groups that have at least one component from each of the first n - 1 cut sets. The augmented table will then consist of "partial" minimal path sets that cover at least the first n cut sets, and cover these sets minimally. Storage requirements for this table vary as additional cut sets are considered, and these requirements may temporarily exceed available main core storage on computers of moderate size. The program has therefore been written to automatically utilize auxiliary storage such as tape or disc when necessary. This is not to imply that the size of the job that can be sucessfully executed is independent of available main core storage; however, in almost all circumstances it appears that the limiting factor in the use of this program for large jobs will be computation time rather than main core storage.

Practical bounds on computation time are extremely difficult to obtain for any given job. A cut set family consisting of 51 cut sets and 24 distinct components has been used for test purposes. Each cut set had 1 to 4 components. About 120 path sets were found, with an average size of 12 components. Computation time on a CDC 6400 with 120K words of core storage was about 20 seconds.

Failure Diagnosis Using Fault Trees

Fault trees can also be used in the failure diagnosis of complex systems. A method for finding minimum time or minimum cost failure diagnosis has recently been discovered at the University of California, Berkeley. This is an area of considerable interest to industries concerned with maintenance costs.

Failure diagnosis can also be described directly in terms of coherent systems; i.e., a system composed of n components that either work or fail, and a Boolean mathematical representation for the system. By testing a system, we mean determining whether or not the system has failed. The object is to determine an optimal sequence for checking the components of the system. Components can be individually tested and it is assumed that tests give perfect information. Also, each test has an associated cost and an a priori probability is given for a component to be functioning. Components are assumed to function or fail independently of each other. The optimal testing policy to be determined can be represented as a decision tree as opposed to a fault tree (or logic tree).

Partial solutions to this problem have been given by Butterworth [8] and Halpern [9]. Using the concept of importance of components, Ben-Dov [10] has developed a branch and bound algorithm which determines the optimal testing policy for any coherent system. By proper identification of terminology, this algorithm can also be used to test the state of the top event for a prescribed fault tree.

Summary

Fault tree analysis is a rapidly developing area of reliability and safety research. Although it is currently being most intensively used by the nuclear power industries and regulatory agencies, it is also beginning to be applied to problems connected with the safety analysis of chemical processing systems, fire safety, seismic risk and other areas of engineering risk evaluation. Sophisticated computer programs and operations research techniques are currently being developed to analyze large, complex fault trees. A recent (June 1977) international conference on nuclear systems, reliability engineering and risk assessment at Gatlinburg, Tennessee, continues to emphasize the increasing importance of this field of research.

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Clearing a Path Through a Minefield

A new capability to rapidly breach a land minefield is nearing completion and soon will be in production through cooperative efforts of the Naval Coastal Systems Laboratory and the Marine Corps Development and Education Command (MCDEC).

The new system, designed, fabricated and successfully tested at the Naval Coastal Systems Laboratory is currently undergoing development test/operational test evaluation by the Amphibious Vehicle Test Branch (AVTB) at Camp Pendleton, California. Installation, operation and maintenance instructions were developed for AVTB by NCSL.

The NCSL-designed system provides for sequential rocket launching of three separate linear charges used to counter land mines. The charge, containing 1750 pounds of explosive, is 350 feet long and is packed into a vertical container, or pallet. Three of the pallets are secured inside an amphibious vehicle LVTP-7 (assault amphibian personnel carrier). A special housing, containing a hydraulically operated rocket launcher equipped with three Mark 22 rockets, is secured over the cargo hatch opening of the LVTP-7.

The LVTP-7, under cover of supporting fire and tactical smoke, moves to a position near the land minefield and deploys one of the charges. As the rocket completes its flight and the charge is emplaced, the fuze automatically arms and a "shorting" wire is broken. The vehicle commander then detonates the charge, clearing a path through a portion of the minefield. The cleared path allows troops or vehicles to move safely through the area.

Research Notes

Hydrogen Isotope Separation Using Plasma Chemistry Technique

Scientists at the Naval Research Laboratory engaged in energy-related research have performed proof-of-principle experiments demonstrating a new, simple method for separating the isotopes of hydrogen.

Their technique may find eventual application in the production of heavy water for nuclear reactors, or for removing radioactive tritium from the effluents of nuclear reactors and nuclear waste reprocessing facilities.

NRL's Christine E. Geosling and Thomas J. Manuccia reported their new technique in a post-deadline paper given at the Joint Canadian Institute of Chemists/American Chemical Society meeting in Montreal, Canada on May 31.

Hydrogen-deuterium enrichment factors exceeding 500% were achieved in a single stage by flowing methane-hydrogen mixtures through a glow discharge operating at low (-105°C) temperatures. The enrichment is a result of an isotopic equilibrium being established between the methane and the molecular hydrogen in which the D/H ratio of the methane is higher than the D/H ratio of the molecular hydrogen.

The large enrichment factors observed are due to the dramatic increase in the above effect as the temperature of the system is lowered, while the novel application of the glow discharge provides active species to keep the rate of isotopic exchange between the two reagents high even at the low temperatures used.

An actual enrichment facility would probably require several stages of enrichment to achieve a large overall enrichment factor. Cascading of the glow discharge process is readily envisioned by removing the hydrogen from the methane-hydrogen mixture emerging from one stage, converting a part of the remaining methane (which is now enriched relative to the input stream) into molecular hydrogen, and using this new mixture as the input to the next stage.

While methane and hydrogen were the reagents used in these experiments, neither of these materials would have to be the actual source of the deuterium or tritium for an enrichment facility. If, for example, the desired isotope were contained in a feed stream of water, both the methane and hydrogen could be run closed-cycle and redeuterated (retritiated) by a variety of methods. Compared to an enrichment stage, redeuteration (retritiation) of a reagent stream is relatively easy to achieve since isotopic selectivity is not required for this process.

While initial experiments were done at low pressures (a few torr), it should be possible, according to Geosling and Manuccia, to scale the process to higher pressures and greatly increased throughputs while retaining the large enrichment factors observed in the laboratory-scale experiments.

Although the initial experiments were not designed in any way to be energy efficient, the NRL researchers were able to estimate an energy cost for a process based only on the initial experimental configuration and the corresponding results. Although this is considerably larger than the energy input the current H_2O/H_2S process requires, they are hopeful that large increases in efficiency should be possible by minimizing known loss processes and by capitalizing on fast, near-thermoneutral radical chain processes to achieve the desired isotope exchange.

For tritium removal, the energy input requirement is of much less concern than it is in large-scale deuterium production, since in this latter case, enormous total volumes of feedstock must be processed.

A supply of nearly pure deuterium, a heavy isotope of hydrogen, is necessary for the production of heavy water, which is required for power generating nuclear reactors using natural abundance uranium (e.g., the Canadian CANDU system). If heavy water is not used, the uranium itself must be enriched.

The glow discharge technique provides large enrichment factors with relatively simple technology. For the H/D application, this technique has the advantage that only non-toxic, easily handled substances are used, whereas the most widely used current industrial process uses H_2S, a poisonous, corrosive gas. For the H/T application, the glow discharge technique avoids the use of unwieldly fractionating columns with large material hold up or catalysts which may be slow acting, expensive, and susceptible to degradation in a radioactive environment. Simplicity and reliability of equipment are especially important in such an environment.

This new isotope separation technique might eventually be developed into an alternative process to those currently performing hydrogen isotope enrichment or purification functions, or, by virtue of its large enrichment factors, be used as a single pre-enrichment stage preceeding a conventional process. Large enrichment factors can also be achieved with laser techniques, however, the high optical powers required, as well as the large energy, capital, and maintenance costs remain serious obstacles to their commercial use at the present time.

A Radar View of Lightning

Mr. James Hughes of the Office of Naval Research (ONR) visited Mr. David Young of Radar Systems, Inc., in North Hollywood. Young is a well known expert in radar technology, having many patents on devices, and has contributed ideas of interest to the Navy. His linear antenna, which can be imbedded throughout the length of a helicopter rotor blade or fixed wing leading edge, is now being considered for mounting on flaps of commercial airliners. Coupled with the rectangular video display of a TV-like screen, this radar provides a rectilinear view of the approach for landing. With support from the ONR Young has made range hyperbolic in time in the scan to achieve convergence at a distance (as railroad rails appear to converge). In this manner, Young has demonstrated equivalence between the radar video display and the pilot's visual view of the runway ahead.

Young's ability to extract the maximum amount of information from a radar sweep has intrigued scientists working with radar in cloud physics. He

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was encouraged to join with physicists working at the Langmuir Observatory in New Mexico during last summer's storm season, with the support of ONR. Young used his prototype radar and display system, which can be mounted in a small aircraft or car, to record the optical and radar return signatures of lightning. In the analysis of data, he has demonstrated that some qualitative information can be obtained about the lightning stroke. With 0.1-microsecond pulses at 100-microsecond intervals in the radar, the rectilinear display produces a series of equally-spaced horizontal bright spots from the radar return of a linear, constant scattering-reflectivity channel. Variations in reflectivity appear as variations in brightness of the spots, and deviations in direction of the channel appear both in the spacing of the spots and in producing spots in adjacent line scans. Multiple lightning strokes produce additional series of spots displaced to other line scans. From this information, some measure of lightning channel geometry and of changes in electron density along the channel may be deduced. Young now has some ideas for demonstrating his technology on charge activity or lightning strokes optically obscured by clouds which could provide information on strokes between charge centers within the cloud. This would be a significant advance in the study of cloud physics.

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IN THIS ISSUE

VOL. XXX, NO. 10

Cover Caption

Measurement of the brain's magnetic field in the unshielded environment of the Neuromagnetism Laboratory at New York University. The SQUID sensor and second derivative gradiometer are immersed in liquid helium contained in the dewar at the upper left.

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