

AD-A264 338



DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

Median is estimated to average 1 hour per release, including the time for reviewing instructions, searching existing data sources, gathering and reviewing the collection of information, sending comments regarding this burden estimate or any other aspect of this collection of information, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Ave., and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188), Washington, DC 20503.

2. REPORT DATE

3. REPORT TYPE AND DATES COVERED

Final Report 01 Apr 92 - 30 Sep 92

4. TITLE AND SUBTITLE

EEG/MEG WORKSHOP

DTIC

ELECTE

MAY 17 1993

5. FUNDING NUMBERS

F49620-92-J-0214

6. AUTHOR(S)

Professor John P Wikswo

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

Vanderbilt University
Department of Physics & Astronomy
Nashville, TN 372358. PERFORMING ORGANIZATION
REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

AFOSR/NE
110 Duncan Avenue, Suite B115
Bolling AFB DC 20332-644810. SPONSORING/MONITORING
AGENCY REPORT NUMBER

2305/GS

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION/AVAILABILITY STATEMENT

UNLIMITED

12b. DISTRIBUTION CODE

13. ABSTRACT (Maximum 200 words)

WORKSHOP WAS HELD

93-10692



14. SUBJECT TERMS

15. NUMBER OF PAGES

16. PRICE CODE

17. SECURITY CLASSIFICATION

UNCLASSIFIED

18. SECURITY CLASSIFICATION

UNCLASSIFIED

19. SECURITY CLASSIFICATION

UNCLASSIFIED

20. LIMITATION OF ABSTRACT

UL

REPORT OF THE 1992 AFOSR WORKSHOP ON THE FUTURE OF EEG AND MEG

John P. Wikswo, Jr.[†], Alan Gevins^{*}, and Samuel J. Williamson[‡]

[†]Living State Physics Group, Department of Physics and Astronomy,
Vanderbilt University, Box 1807 Station B, Nashville, TN 37235

^{*}EEG Systems Lab, 51 Federal St., San Francisco, CA 94107

[‡]Department of Physics, 2 Washington Place, New York University,
New York, NY 10003

Accession for	
NTIS	☒
CRA&I	☐
DTIC	☐
TAB	☐
Unannounced	☐
Justification	
By _____	
Distribution /	
Availability Codes	
Dist	Avail and/or Special
A-1	

I. Introduction

A workshop on the prospects of the electroencephalogram (EEG) and the magnetoencephalogram (MEG) for elucidating human brain function was held at Virginia Beach, Virginia from May 17-22, 1992, and was attended by scientists and physicians from a variety of disciplines, as well as by Federal government officials. Planning for this had been initiated by Drs. Harold Weinstock and Alfred Fregly of the U.S. Air Force Office of Scientific Research in the spring of 1991, and the workshop was organized by the authors of this report.

The purpose of the workshop was to discuss the EEG and the MEG in relation to other rapidly advancing functional imaging modalities such as PET, SPECT, and functional MRI

1 (fMRI), and in terms of the recognized research, medical, and personnel evaluation needs for
2 advanced brain imaging. Medical areas where these and other advanced technologies will
3 undoubtedly be utilized include the diagnosis and treatment of diseases of the brain such as
4 epilepsy, Alzheimer's, and schizophrenia; the monitoring and facilitation of recovery of function
5 from head trauma and stroke, and the quantitative assessment of the effect on the brain of toxins
6 and other bioenvironmental hazards. Non-medical applications of these techniques include a
7 furthering of our understanding of the factors that are limiting the development and full
8 utilization of human intelligence, particularly in recognition of the increasing demands that are
9 being placed on the mental capacities of people who live and work in our modern, post-industrial
10 society.

11 A strong consensus emerged from the workshop that, because of their common
12 electrophysiological source, the EEG and MEG share many features and should be viewed as
13 being complementary methods, both of which will continue to play vital roles in quantitative
14 human neurophysiology because of their unique capabilities for real-time imaging of neuronal
15 activity with millisecond response. There is a great potential for further development of the
16 sensitivity and specificity of these techniques because of continuing increases in the capabilities
17 of computer software, hardware, and visualization technology. These provide, for the first time,
18 the means to process, analyze, and interpret the data from large-scale sensor arrays now being
19 developed. Since fMRI, PET, SPECT, EEG and MEG each have their strengths and
20 weaknesses, and since no single modality can provide complete, real time, functional information
21 throughout the brain, the modalities complement each other and synergistic advances can be
22 expected from their integration.

II. The Controversy

Some controversy recently arose concerning a paper which reported that EEG and MEG produce essentially equal accuracy in localizing point dipole sources represented by sets of electrodes inserted in the human brain (Cohen 1990). This conclusion was countered by criticism that the study was based on obsolete technologies and inadequate procedures (Hari *et al.* 1991, Williamson 1991). The controversy attracted general scientific interest as a news story (Crease 1991; Tepley and Barkley 1991).

Several conferences and symposia have subsequently discussed the topic. The brief report from the European Concerted Action on Biomagnetism (Anogianakis *et al.* 1992) summarized a number of practical differences between the EEG and the MEG, and, in the context of localized sources that can be adequately modeled by a single dipole, delineated the minimum requirements for a satisfactory *in vivo* comparison of the ability to localize dipoles with the EEG and the MEG. The report recognized that more research must be performed before the relative merits of the two methods could be firmly established. However, the approach taken in that report is somewhat restrictive, in that it addresses neither the intrinsic limitations of the dipole model, nor substantive questions regarding the stability and noise-sensitivity of EEG and MEG inverse models.

In a published report of a special symposium at the 1991 meeting of the International Society of Brain Topography, the session chairman Richard Coppola (1991) stated his view that "MEG has to some extent been touted in regard to this localization ability, so that criticism of this ability seems particularly damaging. EEG, on the other hand, has been held to be particularly limited in localization capability. As far as this part of the controversy it appears that we mainly have regression to the mean, MEG may not be a[s] good as expected and EEG

1 turns out better than previously thought." He then went on to indicate that the real potential of
2 both the EEG and the MEG is to reveal the millisecond-to-millisecond dynamics of neural
3 connections. The present workshop was intended to further resolve and go beyond this
4 controversy to discuss more basic scientific issues. In this report from that workshop, we
5 attempt to describe the EEG and MEG from the broader perspective of the multitude of imaging
6 modalities used to study the brain, and to discuss a variety of technical points that must be kept
7 in mind when applying and comparing the EEG and the MEG. We do not attempt to review the
8 latest research findings for either technique.

9 **III. Historical Perspective**

10 To appreciate the relative capabilities of EEG and MEG, it is helpful to consider their
11 recent history. Prior to the introduction of computerized tomography (CT) in the 1960's and
12 magnetic resonance imaging (MRI) in the 1980's, there were few techniques for the non-invasive
13 study of brain anatomy, and only the EEG allowed non-invasive study of brain
14 electrophysiology. In the mid-1980's there was a rapid advance in MEG instrumentation and
15 research as a result of the formation of a critical mass of physical scientists and commercial
16 firms who, for the most part, had not previously been involved with measuring brain function.
17 In part, the impetus for developing MEG instrumentation was provided jointly by the physicists
18 and engineers who, after having developed Superconducting QUantum Interference Device
19 (SQUID) magnetometers primarily for basic research interests, were searching for medical and
20 commercially-sound applications for their new technology, and by neuroscientists who were
21 looking for new methods to study brain function. Having a strong physics orientation, the MEG
22 community focused on characterizing the neural sources of the MEG, which required measuring
23 the fields at many scalp locations. In contrast, during the 1980's the vast majority of electro-

1 encephalographers were neurologists who performed routine clinical examinations using 16 or
2 19 channel recordings and strip chart interpretation procedures that were adequate for the
3 intended purpose and which thus had not substantially changed for several decades. The
4 pressures of clinical duties, the lack of the required technical background, engineering staff and
5 funding generally prevented the clinical EEG community from making any substantive
6 improvements to their instrumentation. Commercial firms added microprocessors to clinical
7 instruments but there were no radical technological advances in clinical EEG instruments.
8 Although computerized topographic mapping was commercially developed in the 1980's, it did
9 not obviate the need for examination of waveform morphology of the EEG traces, and had little
10 impact on clinical practice. Additionally, measurements of evoked potential peak amplitude and
11 latency were routinely used as simple indices of dysfunction, an application which did not
12 require extensive measurement of their spatial features or neural origins. Much of the cognitive
13 research at the time was oriented towards studies of the time course of the evoked potential at
14 a few scalp locations, rather than the spatial dependence of the potential distribution over the
15 entire scalp.

16 Consequently, there was little impetus to extend the capabilities of the EEG towards more
17 detailed spatial mapping. The net result of the difference in culture between the young,
18 quantitatively-oriented MEG community with its emphasis on neural generator models, and the
19 more established, phenomenologically- and clinically-oriented EEG and psychophysiology
20 communities was the comparison of spatially-detailed MEG measurements with ordinary EEGs
21 and evoked potentials. Of course, the EEG was the loser of this "contest". The continued
22 development of the MEG was motivated in part by the fact that the MEG was used to obtain
23 research results that had not yet been found with the EEG, possibly because the vast majority

1 of EEG practitioners were not interested in developing the level of technical or mathematical
2 sophistication that had already been brought to bear on the MEG. Eventually, EEG researchers
3 rediscovered that if measurements were made at more locations, the EEG could also be
4 effectively used for dipole source modeling, and the controversy inevitably ensued.

5 Meanwhile, magnetic resonance imaging (MRI), Positron Emission Tomography (PET),
6 and Single Photon Emission Computer Tomography (SPECT) techniques had been extended to
7 allow the study of brain function and provided impressive three-dimensional images of the brain
8 and certain aspects of its activity. As a result there are now multiple modalities competing for
9 both research funds and potential clinical income. Vocal proponents of each modality have been
10 known to denigrate other methods as being technically inferior or unnecessarily costly. Few
11 investigators use multiple modalities, and objective comparisons have been slow to appear.

12 **IV. Focus of the Workshop**

13 At the outset of the AFOSR workshop, the organizers set a constructive tone by noting that
14 the principals in the controversy had made their points a sufficient number of times, and that
15 further argument without new data was pointless. Instead, the goal of the workshop was to
16 develop a detailed assessment of the future directions for both the EEG and the MEG, and to
17 assess the significance of ongoing theoretical and experimental developments pertinent to each
18 technique in light of the other high-technology approaches for studying the brain. The topics
19 discussed included the theoretical and practical aspects of the MEG and EEG, inverse problems,
20 multimodality integration, clinical considerations and applications, perception and cognition, and
21 the future. Rather than present a chronological account of the workshop, it is more useful to
22 synthesize what was learned into a critical assessment of the EEG and MEG.

1 Comparison with other techniques.

2 The EEG and the MEG are the only techniques that offer millisecond response to brain
3 events, in comparison to the 40 second response and several millimeter resolution offered by
4 oxygen 15 PET. Recent advances in fMRI techniques permit 1-2 mm spatial resolution and
5 several second time resolution of cerebral blood volume. There is currently a very rapid
6 development of functional MRI techniques that allow measurement of changes in blood volume
7 and other vascular-related phenomena throughout the whole head. While an fMRI image can
8 be obtained in as short a time as 50 ms, the temporal resolution is limited by the much longer
9 time constant for blood diffusion, approximately 2 seconds or more.

10 Enthusiasm about the high temporal resolution of EEG and MEG relative to other imaging
11 modalities is tempered by the fact that there is no need to solve an ill-conditioned inverse
12 problem in the case of PET, SPECT and fMRI, even though each of these techniques involve
13 detailed mathematical calculations with their own inherent restrictions. PET and SPECT can
14 image a wide variety of radioactively-labelled substances administered to the brain, and PET,
15 SPECT, and fMRI can all image vascular events, none of which are possible with either EEG
16 or MEG. Undoubtedly, PET and SPECT will find continued utilization in imaging
17 neurochemistry and following the kinetics of receptor uptake over periods ranging up to hours.

18 With regard to cost, none of these advanced techniques is inexpensive, either in terms of
19 hardware or staff. Of all of the techniques considered, the EEG is by far the least expensive,
20 followed by SPECT, MEG, functional MRI, and finally PET. Given this larger perspective,
21 the issue for the remainder of this report is to understand the strengths and weaknesses of both
22 the EEG and MEG.

1 Advances in MEG and EEG Instrumentation and Measurement Techniques.

2 Novel MEG and EEG recording technologies currently under development will each
3 markedly reduce the amount of time needed to obtain spatially detailed recordings over the
4 whole head. The first full-scalp 122 channel MEG system is presently coming on line (Ahonen
5 *et al.*, in press), and the Ministry of International Trade and Industry (MITI) in Japan has
6 initiated a ten-company industrial collaboration to develop a 200 channel system at the new
7 Superconducting Sensor Laboratory. Such multichannel systems obviate the need to make
8 separate recordings at a number of sites, and are expected to reduce recording time by more than
9 a factor of five over current commercial 37 channel systems. Moreover, signal quality will
10 improve by more than a factor of 3 because the current limitation is imposed by "brain noise".
11 That is, the magnetic field from adjacent areas of the brain are much stronger than instrument
12 noise, so that when this activity can be taken into account by comprehensive simultaneous
13 sampling of the field pattern everywhere across the scalp, the net noise level will be markedly
14 reduced. The fixed geometric arrangement of the sensors will simplify mathematical analysis
15 of the signals, but will lead to some loss in signal quality if the head is too small to fill the
16 detector and closely couple to each SQUID sensor. The ability to record from all channels
17 simultaneously will represent a major advance in the ability to map spontaneous events that
18 cannot be reconstructed from serial measurements.

19 Several advances in EEG instrumentation that should simplify potential mapping were
20 reported at the workshop. These include a 128-channel EEG Geodesic Electrode Net which can
21 be applied in about ten to fifteen minutes (Tucker, public communication), and a 32-channel
22 EEG recording hat with active electrodes that allows rapid setup for recordings (less than 5
23 minutes) without any preparation of the scalp (Gevins, DuRousseau and Libove 1991). Such

1 systems would offer the community many of the advantages claimed by proponents of the
2 multichannel MEG.

3 Undoubtedly, further technical advances should be expected for both the EEG and MEG,
4 particularly when used in combination with each other or with other imaging techniques such
5 as MRI. Already, the EEG and/or MEG are being integrated with individual MRI slices and
6 three-dimensional MRI images for both research (Gevins 1987; Gevins 1989; Williamson *et al.*
7 1991) and clinical studies (Galen *et al.*, in press). With the availability of commercial software
8 packages for image analysis and registration, it will be increasingly easy for more investigators
9 to compare and integrate data from several modalities.

10 An often-stated merit of the MEG is that it represents a reference-free recording of the
11 magnetic field at a single location, whereas the EEG is a measurement of a potential difference
12 between two electrodes, one of which is generally at a fixed reference location. There have
13 been many studies that demonstrate that EEG waveforms are sensitive to the location of the
14 reference electrode, and, as a result, individual investigators have their own preference for
15 reference electrode configurations, which include the potential obtained by linking both ears and
16 the potential computed by averaging across all electrodes. The situation is complicated by the
17 fact that commonly the reference potential is not neutral because an electrode on which it is
18 based may have its own electric activity. For example, reference electrodes on the ear are close
19 to the auditory cortex. If a reference electrode is placed on the body, the recordings may be
20 subject to increased noise and muscle artifact.

21 The requirement for a reference electrode can be overcome by computing the surface
22 Laplacian, performed, in its simplest form, by subtracting from a given recording one-fourth of
23 the voltage signal recorded at each of the four surrounding electrodes to evaluate the $\partial^2 V / \partial x^2$

1 $+ \partial^2 V / \partial y^2$. The resulting Laplacian EEG maps are substantially sharper than the original EEG
2 potential maps, for they reveal the pattern where volume current emerges from the cortex and
3 passes through the skull into the scalp, and where it returns to the interior.

4 Such a presentation may be helpful in suggesting by visual inspection the locations of
5 underlying sources. However, the sharper pattern does not in itself imply that a more accurate
6 inverse solution for the sources can be obtained. It has been shown using a volume conductor
7 model for activity from a single axon that the computation of a spatial derivative of the
8 extracellular potential, corresponding to filtering out the low spatial frequencies, will sharpen
9 the potential pattern but will also make it more difficult to perform the inverse calculation of
10 determining the actual source configuration from the potential data (Roth and Wikswo 1985).

11 The trade-off is between the advantages of the sharpened potential maps and the elimination of
12 reference electrode effects, and the disadvantages of reduced sensitivity to deep sources,
13 uncertainties in scalp and skull conductivities, the inability to compute the full Laplacian at the
14 edges of the electrode array, and the possibility of increased instability in the inverse calculation.

15 A more fruitful approach to spatially sharpening the EEG explicitly corrects the blurring due to
16 conduction through the skull and other tissues (Gevins *et al.* 1991; Le and Gevins, in press).

17 A similar Laplacian approach can be applied to the MEG, providing a sharpened pattern by
18 either mathematical subtractions or by using planar gradiometers that measure field differences
19 at adjacent locations on the scalp, but this will also be subject to many of the same limitations
20 as the EEG Laplacian.

21 The EEG and MEG Inverse Problems.

22 Once a map of the electric or magnetic field over the surface of the scalp has been
23 recorded, an investigator can apply pattern recognition techniques and knowledge of the location

1 of each electrode to interpret the underlying event, as has been done in clinical EEG for
2 decades. Alternatively, a mathematical model of the scalp-recorded EEG can be used to obtain
3 more detailed information about the spatial location of the source (Kavanagh 1972). One of the
4 great successes in this approach was the early MEG studies that showed how a clear magnetic
5 field pattern recorded on the scalp could be correlated, by means of a very simple mathematical
6 model with focal, dipolar current sources located in underlying cortical fissures (Williamson and
7 Kaufman 1981).

8 Were the head and brain perfect concentric spheres, the EEG would be able to detect both
9 radial and tangential dipoles, but the MEG, being insensitive to radial dipoles, would be able
10 to discriminate between two hypothesized sources, one of which had a tangential component and
11 the other of which did not (Hari *et al.* 1984; Wood *et al.* 1985). However, since the skull and
12 brain do not form perfectly concentric homogenous shells, the selectivity of the MEG is
13 somewhat compromised, and dipoles oriented normal to the skull may contribute appreciably.
14 Although not physiologically realistic, point dipole models may prove to be useful in certain
15 clinical applications. For example, magnetic location of the somatosensory strip in three
16 dimensions can help guide surgical planning for removal of tumors that have displaced the strip
17 from its normal locus (Galen *et al.*, in press).

18 In determining dipoles, there are practical differences between MEG and EEG. To a first
19 approximation, the MEG recorded above the scalp is determined primarily by the configuration
20 and strength of the current sources within the brain and not by the electrical properties of the
21 intervening media. This is a result of biological tissue being transparent to magnetic fields,
22 being capable of distorting electric fields.

1 In a more accurate treatment of the MEG, the distortions in the currents within the brain,
2 skull, and scalp, as compared to those flowing in an ideal, spherical skull, will also produce
3 magnetic fields, but these fields are typically only a fraction of the magnetic field that comes
4 directly from the bioelectric sources within the brain. For example, an MEG inverse model
5 applied to frontal sources was shown to require knowledge only of the brain shape, whereas
6 corresponding accuracy could be obtained for the EEG only with a model that included the
7 geometry and conductivity of not only the brain but also the skull and scalp (Hämäläinen *et al.*
8 1989; Meijis and Peters 1987; Meijis *et al.* 1989). It is standard practice in EEG dipole analysis
9 to take inhomogeneities into account through the use of multi-shell head models (Fender 1987).

10 The Limitations of the Dipole Model. Much of the MEG research and most of the ongoing
11 controversy regarding the EEG and MEG has centered on the current dipole model for brain
12 activity. While this model may be appropriate for simple sensory stimuli, there are important
13 examples where it may be inadequate. For example, the cortical surface associated with an ictal
14 or interictal epileptic spike can be as large as several tens of square centimeters and might better
15 be described by an extended area than by a point dipole. Also, even simple mental tasks involve
16 widely distributed neural networks. An interesting difficulty arises when a simple dipole model
17 is applied to explain fields from such an extended source. If the density of dipoles within the
18 layer is constant, and the dipoles are everywhere oriented normal to the layer, the source is
19 termed a uniform double layer. For such sources, the electric and magnetic fields will be
20 determined primarily by the shape and location of the boundary of the double layer, and the
21 detailed geometry of the layer within the boundary will affect neither signal (Wikswa 1983).
22 A single dipole fit for either EEG or MEG data will have a location and components that
23 correspond to the center of mass and projected areas of the rim of the extended double layer.

1 In actuality, the spatial distribution of active current sources will be non-uniform, so the electric
2 and magnetic fields will also be affected by the detailed shape of the curved surface within the
3 boundary. The major practical problem with dipole modeling of extended neural sources is that
4 the actual number of dipoles cannot be statistically determined from the data. This follows from
5 the fact that many different source configurations can produce the same EEG or MEG field
6 pattern at the scalp.

7 Constrained Models. While it is not possible, in principle, to overcome the inherent
8 limitations of EEG and MEG in terms of general three-dimensional imaging throughout the
9 brain, there are mathematical techniques to force a solution from a potentially-unstable, ill-
10 conditioned inverse calculation. A variety of minimum norm approaches have been utilized to
11 obtain three-dimensional images of purported currents in the brain from MEG maps (Ioannides
12 *et al.* 1990; Ribary *et al.* 1991; Hämäläinen and Ilmoniemi 1992), but the constraints applied
13 to the inverse calculation may provide stable solutions of questionable physiological
14 interpretation. Similar comments apply to the method of singular value decomposition which
15 shows that in certain circumstances it is possible to extract localized information from a
16 complex, widely distributed potential field (Harner and Riggio 1989; Harner 1990). There have
17 yet to be any validations of the results obtained with such an algorithm by means of a
18 quantitative comparison with subdural potential distributions or current source density analysis.

19 A potentially more realistic approach is to incorporate into the model physiological
20 constraints that were determined by other measurement modalities, such as MRI, fMRI, PET,
21 or SPECT. For example, a recent model assumed a configuration for the cortical surface in a
22 fissure or sulcus and applied a constraint that the primary currents would be perpendicular to
23 the dipole surface. It was shown that in principle it will be possible to use magnetic data to

1 obtain a best estimate for the pattern of activity distributed across broad areas of the cerebral
2 cortex for arbitrary configurations of activity (Wang *et al.* 1992). Models that incorporate both
3 temporal and spatial constraints or measures of covariance may be even more powerful.

4 Ideally, techniques will be developed that will allow the sharpening of the EEG and the
5 MEG with minimal use of physiologically-constrained models, since such models may introduce
6 bias or errors if the signals were, in fact, affected by an unknown brain pathology. The surface
7 Laplacian approach is a step in this direction, as are EEG inward continuation approaches that
8 go further to compute the potential distribution on the dura just inside the inner surface of the
9 skull, or even further inward if there is prior knowledge about the number, location or geometry
10 of the sources (Gevins *et al.*, 1991 and Gevins *et al.*, in press). Similar approaches have been
11 proposed for the MEG (Nicolas and Kouwenhoven 1989; Tan, Roth and Wikswo 1990), but
12 have not yet been implemented. Once the inward-continued potential or magnetic field at the
13 dura has been computed, with the associated sharpening of the map features, it is sometimes
14 possible to review the data and ascertain whether a particular physiologically-based model would
15 be appropriate.

16 Testing our understanding of the EEG and MEG relationship.

17 Although there has been much discussion of the relative abilities of the EEG and the MEG
18 to locate a dipole, the issues, as outlined in this report, are in fact much broader. The issues
19 include: how to treat multiple close-lying sources and extensive sources that cannot be properly
20 modeled by a single dipole or an ensemble of two or three dipoles; how to gauge the effects of
21 external and brain noise on inverse algorithms; how to incorporate physiological and anatomical
22 constraints to inverse calculations, as well as the role of anisotropies in the electrical
23 conductivity of brain tissues, and whether quantitative measurements of absolute source strength

1 have diagnostic utility. Absolute source strengths are often deduced in MEG studies, while in
2 EEG studies relative source strengths are computed due to lack of knowledge of tissue
3 conductivities. The best scientifically-sound means to ascertain whether the inverse models are
4 producing realistic results and to test the EEG/MEG relationship is to compare the models with
5 intracerebral data from neurosurgery patients (Cohen *et al.* 1990; Balish *et al.* 1991; Sutherling
6 and Barth 1989) or to use animal models (Barth and Di 1990; Gardner-Medwin, *et al.* 1991;
7 Huang *et al.* 1990; Okada *et al.* 1987; Okada *et al.* 1988; Okada, in press).

8 Applications of EEG and MEG to Cognitive Science.

9 Some cognitive scientists recognize a need for more sophisticated network models and more
10 clever experimental designs to deal with the complexities of widely distributed neural processes.
11 An opinion was expressed that studies of event-related responses have had little impact on the
12 development of cognitive science, because very few of them address issues of prime interest to
13 the cognitive community. However, the use of a large array of EEG electrodes now makes it
14 possible to determine sub-second functional associations between cortical areas characterizing
15 working memory and other basic cognitive functions (Gevins *et al.* 1981; Gevins *et al.* 1983).
16 Such studies demonstrate the necessity of understanding post-stimulus cognitive processing in
17 the context of the subject's internal model for the environmental conditions and specified task
18 (Gevins *et al.* 1987). In the past, MEG applications were also hindered by the lack of large
19 sensor arrays, but here as well the development of arrays of 37 and 122 sensors has overcome
20 this obstacle. But even without instruments with many sensors, it is possible to conduct useful
21 research by locating the position of a neural source and then placing the instrument to obtain the
22 strongest signal. This advantage was exploited in a recent study of habituation in the primary
23 and association auditory cortices in which evidence was obtained that the neuronal activation

trace has a markedly shorter lifetime in the primary cortex than in the association cortex (Lu *et al.* 1992) and correlates with the lifetime of echoic memory (Lu *et al.*, in press). While the new technologies make it possible to monitor many EEG and MEG channels, in practice the knowledge gained from studies in cognition is less dependent upon the sophistication of the hardware used by the investigator than upon the skill of the investigator in devising an appropriate paradigm and unravelling the resulting data!

V. Conclusion

It is unlikely that the differential sensitivities of the MEG and EEG to radial versus tangential sources is of sufficient importance alone to significantly influence the relative ranking and utility of the EEG and the MEG. The main advantages of the MEG follow from the fact that MEG signals are not highly distorted by conduction through the skull between sensors and scalp. The main disadvantages are that the subject can not move during a recording and the technology is at present expensive and requires a massive magnetically-shielded room. While magnetic contamination poses serious difficulties, the MEG can also be used to detect non-invasively DC shifts associated with phenomena ranging from spreading depression to head injury (Barkley *et al.* 1991; Gardner-Medwin *et al.* 1991).

Conversely, the main advantage of the EEG is that it is inexpensive and can be recorded in a natural environment. The EEG is also better suited for studies of the brainstem because the sources are deep, making them difficult to detect with the MEG. The major disadvantage of the EEG is that detailed information about the external and internal geometry of a subject's head is needed to correct for spatial blur from conduction through the skull. Also, it is necessary to establish good electrical contact with the skull, but this is less of a problem with high impedance active electrodes (Gevins, DuRousseau and Libove 1991).

Coppola (1991) points out that at present a multichannel, clinical MEG system costs about 25 times more than an EEG system with a similar number of channels, and the potential benefit to a patient must justify this cost differential. However, he notes that the issue of cost is different for a research environment, where the additional information gained may justify the cost, particularly if there is no other way to obtain this information. Substantial costs for technicians to apply 128 EEG electrodes by traditional techniques may well be cut dramatically by the advent of high impedance amplifiers and simpler procedures for securing electrodes (Gevins, DuRousseau and Libove 1991).

A large number of device- and modeling-oriented research groups worldwide have invested heavily in developing the MEG as a quantitative technique for assessing brain function. Unfortunately, because of the constraints imposed by accepted clinical practice and the historical bias regarding the limitations of the EEG, there has been substantially less effort directed towards pressing EEG recording and analysis techniques to their theoretical limits. Cross-fertilization of the efforts between the two communities should lead to substantive improvements in both techniques.

When both the MEG and the EEG, as well as their users, are at the same level of technical and physiological sophistication, it will undoubtedly be possible to obtain additional returns on the collective intellectual investments by fully merging the two techniques to obtain even more accurate and stable source reconstructions, as was done using single-channel SQUIDS several years ago (Wood *et al.* 1985).

Both the MEG and the EEG are expected to undergo further development in the next few years. Extension of the capabilities of the EEG is within easy reach, particularly once techniques are devised for automatic placement of up to 256 electrodes and effective artifact

1 recognition. The future of the MEG lies with the large, whole-scalp multichannel SQUID
2 systems. Advanced noise rejection, signal processing, and source-characterization algorithms
3 will benefit both approaches. In response to the need to improve the diagnosis and treatment
4 of neurologic and psychiatric diseases, rapid development of several other technologies that
5 measure complementary aspects of brain anatomy and function is taking place concomitantly,
6 especially including PET and SPECT, and fMRI for structure and function. Since all of these
7 imaging modalities have their strengths and weaknesses, and since no single modality can
8 provide complete, real time, functional information throughout the brain, the modalities are truly
9 complementary.

10 Moreover, synergistic advances can be expected from the integration of the EEG and MEG
11 with the other modalities. Intercomparison of data obtained by EEG and MEG with
12 complimentary studies using invasive electrodes in patients, or PET, SPECT, and fMRI in
13 patients and normal subjects will provide important validations across modalities. Animal
14 models and tissue preparations will provide additional validation at a more detailed and better
15 controlled level.

16 As Hans Berger had hoped, human neurophysiology can serve as a "window on the mind"
17 by performing real-time imaging of mental functions of the brain. This Holy Grail of our field
18 is much closer to realization than was thought possible even a few years ago.

19 Acknowledgements

20 The Workshop and the preparation of this manuscript were funded by Grant F49620-92-J-
21 0214 from the Air Force Office of Scientific Research. We are indebted to Cheryl Cosby, Rashi
22 Abbas, Alan Bradshaw, and Danny Staton for handling the numerous administrative and practical
23 details associated with the Workshop.

References

- Ahonen, A.I., Hämäläinen, M.S., Kajola, M.J., Knuutila, J.E.T., Laine, P.P., Lounasmaa, O.V., Simola, J.T., Tesche, C.D., and Vilkmann, V.A. "A 122-channel magnetometer covering the whole head," Proc. IEEE EMBS Satellite Symposium on Neuroscience and Technology, in press.
- Anogianakis, G., Badier, J.M., Barrett, G., Ern , S., Fenici, R., Fenwick, P., Grandori, F., Hari, R., Ilmoniemi, R., Maugu  re, Lehmann, D., Perrin, F., Peters, M., Romani, G.-L., and Rossini, P.M. "A consensus statement on relative merits of EEG and MEG," Editorial. Electroenceph. Clin. Neurophysiol. 1992, 82: 317-319.
- Balish, M., Sato, S., Connaughton, P., and Kufta, C. "Localization of implanted dipoles by magnetoencephalography," Neurology 1991, 41: 1072-1076.
- Barkley, G.L., Moran, J.E., Takanashi, Y., and Tepley, N. "Techniques for DC magnetoencephalography," J. of Clin. Neurophysiol., 1991, 8(2): 189-199.
- Barth, D.S. and Di, S. "The electrophysiology basis of epileptiform magnetic field in neocortex: Spontaneous ictal phenomena," Brain Res., 1990, 530: 35-39.
- Cohen, D., Cuffin, B.N., Yunokuchi, K., Maniewski, R., Purcell, C., Cosgrove, G.R., Ives, J., Kennedy, J.G., and Schomer, D.L. "MEG versus EEG localization test using implanted sources in the human brain. Ann. Neurol., 1990, 28: 811-817.
- Coppola, R. "Regression to the Mean," Brain Topography, 1991, 4(2): 81-83.
- Crease, R.P. "Images of Conflict: MEG vs. EEG," Science, 1991, 253: 374-375.
- Fender, D.H. "Source localization of brain electrical activity," in Methods of Analysis of Brain Electrical and Magnetic Signals; Handbook of Electroencephalography and Clinical

1 Neurophysiology, A.S. Gevins and A. Remond, Eds., (Elsevier, Amsterdam, 1987), Vol.
2 1, pp. 355-403.

3 Galen, C.C., Schwartz, B., Rieke, K., Pantev, C., Sobel, D., Hirschkoff, E., and Bloom, F.E.
4 "Intrasubject reliability and validity of somatosensory source localization using a large
5 array biomagnetometer," Electroenceph. Clin. Neurophysiol., in press.

6 Gardner-Medwin, A.R., Tepley, N., Barkley, G.L., Moran, J., Nagel-Leiby, S., Simkins,
7 R.T., and Welch, K.M.A. "Magnetic fields associated with spreading depression in
8 anesthetized rabbits," Brain Res., 1991, 940: 153-158.

9 Gevins, A.S. "Obstacles to progress," in Methods of Analysis of Brain Electrical and Magnetic
10 Signals: Handbook of Electroencephalography and Clinical Neurophysiology, A.S. Gevins
11 and A. Remond, Eds., (Elsevier, Amsterdam, 1987), Vol. 1, pp. 665-673.

12 Gevins, A.S. "Dynamic functional topography of cognitive tasks," Brain Topography, 1989,
13 2(1/2): 37-56.

14 Gevins, A.S., DuRosseau, D., and Libove, J. "Electrode system for brain wave detection,"
15 Patent 5,038,782, August 13, 1991.

16 Gevins, A.S., Le, J., Brickett, P., Reutter, B., and Desmond, J.E. "Seeing through the skull:
17 Advanced EEGs use MIRs to accurately measure cortical activity from the scalp," Brain
18 Topography, 1991, 4(2): 125-131.

19 Gevins, A.S., Brickett, P., Le, J., Martin, N., Desmond, J.E., and McLaughlin, J. "124-
20 channel recording, spatial enhancement and MRI integration methods," Electroenceph.
21 Clin. Neurophysiol., in press.

- 1 Gevins, A.S., Schaffer, R.E., Doyle, J.C., Cutillo, B.A., Tannehill, R.L., and Bressler, S.L.
- 2 "Shadows on thought: Shifting lateralization of human brain electrical patterns during brief
- 3 visuomotor task," Science, 1983, 220: 97-99.
- 4 Gevins, A.S., Doyle, J.C., Cutillo, B.A., Schaffer, R.E., Tannehill, R.S., Ghannam, J.H.,
- 5 Gilcrease, V.A., and Yeager, C.L. "Electrical potentials in human brain during cognition:
- 6 New method reveals dynamic patterns of correlation," Science, 1981, 213: 918-922.
- 7 Gevins, A.S., Morgan, N.H., Bressler, S.L., Cutillo, B.A., White, R.M., Illes, J., Greer,
- 8 D.S., Doyle, J.C., and Zeitlin, G.M. "Human neuroelectric patterns predict performance
- 9 accuracy," Science, 1987, 235: 580-585.
- 10 Hämäläinen, M.S. and Ilmoniemi, R.J. "Interpreting magnetic fields of the brain: Minimum-
- 11 norm estimates," IEEE Trans. Biomed. Eng., 1992, submitted.
- 12 Hämäläinen M.S. and Sarvas J. "Realistic conductivity geometry model of the human head for
- 13 interpretation of neuromagnetic data," IEEE Trans. Biomed. Eng., 1989, 36: 165-171.
- 14 Hari, R., Hämäläinen, M., Ilmoniemi, R., and Lounasmaa, O.V. "Comment on 'MEG versus
- 15 EEG localization test using implanted sources in the human brain'," Letter to the Editor.
- 16 Ann. Neurology, 1991, 30: 222-223.
- 17 Hari, R., Reinikainen, K., Kaukuroanta, E., Hämäläinen, M.S., Ilmoniemi, R., Penttinen, A.,
- 18 Salminen, J., and Teszner, D. "Somatosensory evoked cerebral magnetic fields from SI
- 19 and SII in man," Electroenceph. and Clin. Neurophysiol., 1984, 57: 254-263.
- 20 Harner, R.N. "Singular value decomposition - A general linear model for analysis of
- 21 multivariate structure in the electroencephalogram," Brain Topography, 1990, 3: 43-47.
- 22 Harner, R.N. and Riggio, S. "Application of singular value decomposition to topographic
- 23 analysis of flash-evoked potentials," Brain Topography, 1989, 2: 91-98.

- 1 Huang, J.-C., Nicholson, C., and Okada, Y. "Distortion of magnetic evoked fields and surface
2 potentials by conductivity differences at boundaries in brain tissue," Biophys. J., 1990, 57:
3 1155-1166.
- 4 Ioannides, A.A., Bolton, J.P.R., and Clarke, C.J.S. "Continuous probabilistic solutions to the
5 biomagnetic inverse problem," Inverse Problems, 1990, 6: 523-542.
- 6 Kavanagh, R.N. "Localization of sources of human evoked responses," Ph.D. Thesis,
7 California Institute of Technology, Pasadena, CA, 1972.
- 8 Le, J. and Gevins, A.S. "Method to reduce blur distortion from EEGs using a realistic head
9 model," IEEE Trans. Biomed. Eng., in press.
- 10 Lu, Z.-L., Williamson, S.J., and Kaufman, L. "Human auditory primary and associated cortex
11 have differing lifetimes for activation traces," Brain Res., 1992, 527: 236-241.
- 12 Lu, Z.-L., Williamson, S.J., and Kaufman, L. "Physiological measures predict behavioral
13 lifetime of human auditory sensory memory," Science, in press.
- 14 Meijis, J.W.H. and Peters, M.J. "The EEG and MEG, using a model of eccentric spheres to
15 describe the head," IEEE Trans. Biomed. Engr., 1987, 34: 913-920.
- 16 Meijis, J.W.H., Weier, O.W., Peters, M.J., and van Oosterom, A. "On the numerical
17 accuracy of the boundary element method," IEEE Trans. Biomed. Engr., 1989, 36: 1038-
18 1949.
- 19 Nicolas, P. and Kouwenhoven, M. "Spatial filtering in multichannel magnetoencephalography,"
20 J. Biomed. Eng., 1989, 11: 79-86.
- 21 Okada, Y.C. "Magnetophysiology as an emerging discipline in neuroscience," Proc. of the
22 22nd Annual Meeting of EEG and EMG, Tokyo, in press.

- 1 Okada, Y.C., Lauritzen, M., and Nicholson, C. "Magnetic field associated with neural
2 activities in an isolated cerebellum," Brain Res., 1987, 412: 151-155.
- 3 Okada, Y.C., Lauritzen, M., and Nicholson, C. "Magnetic field associated with spreading
4 depression: A model for the detection of migraine," Brain Res., 1988, 412: 185-190.
- 5 Ribary, U., Ioannides, A.A., Singh, K.D., Hasson, R., Bolton, J.P.R., Lado, F., Mogilner,
6 A., and Llinás, R. "Magnetic field tomography of coherent thalamocortical 40-Hz
7 oscillations in humans," Proc. Natl. Acad. Sci. USA, 1991, 88: 11037-11041.
- 8 Roth, B.J. and Wikswo, J.P., Jr. "The magnetic field of a single axon: A comparison of theory
9 and experiment," Biophys. J., 1985, 48: 93-109.
- 10 Sutherling, W.W. and Barth, D.S. "Neocortical propagation in temporal lobe spike foci on
11 magnetoencephalography and electroencephalography," Ann. Neurol., 1989, 25: 373-381.
- 12 Tan, S., Roth, B.J., and Wikswo, J.P. Jr. "The magnetic field of cortical current sources: The
13 application of a spatial filtering model to the forward and inverse problems,"
14 Electroenceph. and Clin. Neurophysiol., 1990, 76: 73-85.
- 15 Tepley, N. and Barkley, G.L. "Wave of the Future," Science, 1991, 253: 1468.
- 16 Wang, J.-Z., Williamson, S.J., and Kaufman, L. "Magnetic source images determined by a
17 lead-field analysis: The unique minimum-norm least-squares estimation," IEEE Trans.
18 Biomed. Engr., 1992, 39: 665-675.
- 19 Wikswo, J.P., Jr. "Theoretical aspects of the ECG-MCG relationship," in Biomagnetism, An
20 Interdisciplinary Approach, S.J. Williamson, G.-L. Romani, L. Kaufman and I. Modena,
21 Eds., (Plenum, New York, 1983), pp. 311-326.
- 22 Williamson, S.J. "MEG versus EEG localization test," Letter to the Editor. Ann. Neurology,
23 1991, 30: 222.

1 Williamson, S.J. and Kaufman, L. "Magnetic fields of cerebral cortex," In: "Biomagnetism",
2 S.N. Erne, H.-D. Hahlbohm, and H. Lubbig, Eds., (Walter de Gruyter, Berlin, 1981), pp.
3 432-444.

4 Williamson, S.J., Lu, Z.-L., Karon, D., and Kaufman, L. "Advantages and limitations of
5 magnetic source imaging," Brain Topography, 1991, 4: 169-180.

6 Wood, C.C., Cohen, C., Cuffin, Yairita, M., Allison, T. "Electrical sources in human
7 somatosensory cortex: Identification by combined magnetic and potential recordings,"
8 Science, 1985, 227: 1051-1053.

LIST OF ATTENDEES

†Organizing Committee

***Graduate Student Assistants**

Rashi Abbas*

Living State Physics Laboratory
Department of Physics and Astronomy
Vanderbilt University
Box 1807 Station B
Nashville, TN 37235

Gregory L. Barkley, M.D.
Department of Neurology, K-11
Henry Ford Hospital
2799 West Grand Blvd.
Detroit, MI 48202-2689
Office: (313) 876-3922
Fax: (313) 876-2187

Dr. Daniel S. Barth
Department of Psychology
Campus Box 345, Muenzinger Bldg.
University of Colorado
Boulder, CO 80309-0345
Office: (303) 492-8662
Fax: (303) 492-2967

Alan Bradshaw*
Living State Physics Laboratory
Department of Physics and Astronomy
Vanderbilt University
Box 1807 Station B
Nashville, TN 37235

Dr. Lynn Cooper
Department of Psychology
Columbia University
New York, NY 10027
Office: (212) 854-2039
Fax: (212) 854-3609

Dr. Richard Coppola
NIMH Neuroscience Center
St. Elizabeths
Washington, DC 20032
Office: (202) 373-6222

Fax: (202) 373-6214

Dr. John S. Ebersole
V.A. Medical Center
Neurology Service (127)
950 Campbell Avenue
West Haven, CT 06516
Office: (203-932-5711 Ext. 724
Fax: (203) 932-5711 Ext. 2609

Dr. Al Fregly†
12703 Mac Duff Drive
Fort Washington, MD 20744
Phone: (301) 292-3313

Christopher C. Gallen, M.D.
Biomagnetism Laboratory
The Scripps Research Institute
10666 N. Torrey Pines Road - BCR1
La Jolla, CA 92037
Office: (619) 554-8563
Fax: (619) 554-6288

Dr. Alan S. Gevins†
EEG Systems Laboratory
51 Federal Street, Suite 401
San Francisco, CA 94107
Office: (415) 957-1600, Ext 133
Fax: (415) 546-7122

Dr. Matti Hämaläinen
Low Temperature Laboratory
Helsinki University of Technology
Rakentajanaukio 2
SF-02150 Espoo, FINLAND
Office: 358-0-451-2961
Fax: 358-0-451-2969

Dr. Richard N. Harner
Department of Neurology
Robert Wood Johnson Medical School
New Brunswick, NJ 08901

Office: (908) 937-7733
Fax: (908) 418-8041

Dr. Lloyd Kaufman
Department of Psychology
New York University
6 Washington Place
New York, NY 10003
Office: (212) 998-7878
Fax: (212) 995-4011

Dr. Paul C. Lauterbur
Biomedical Magnetic Resonance Lab
University of Illinois
1307 W. Park St.
Urbana, IL 61801
Office: (217) 244-0600
Fax: (217) 244-1330

Dr. George Lawrence
Army Research Institute
5001 Eisenhower Ave.
Alexandria, VA 22333
Office: (703) 274-8293
Fax: (703) 274-5616

Dr. Richard Nakamura
NIMH, Room 11-102
Parklawn Bldg.
5600 Fishers Lane
Rockville, MD 20857
Office: (301) 443-1576
Fax: (301) 443-4822

Dr. Paul Nunez
622 Seabright Lane
Solana Beach, CA 92075
Phone: (619) 481-3063
Fax: (619) 481-7949

Dr. Yoshio Okada
Director, MEG Center (101)
V.A. Medical Center
2100 Ridgecrest Drive SE
Albuquerque, NM 87108
Office: (505) 256-2874
Fax: (505) 256-2859

Dr. D. Martin Regan
Psychology Department Faculty of Arts
Behavioural Sciences Bldg.
York University
4700 Keele Street
North York, CANADA M3J 1P3
Office: (416) 736-5627
Fax: (416) 736-5814

Dr. Stephen Robinson
MEG Center
V.A. Medical Center
2100 Ridgecrest Drive SE
Albuquerque, NM 87108
Office: (505) 265-1711
Fax: (505) 256-2859

Dr. Susumu Sato
NINDS
National Institutes of Health
Bldg. 10, Room 5C101
Bethesda, MD 20892
Office: (301) 496-5121
Fax: (301) 496-1675

Danny Staton*
Living State Physics Laboratory
Department of Physics and Astronomy
Vanderbilt University
Box 1807 Station B
Nashville, TN 37235

Dr. William W. Sutherling
Department of Neurology
UCLA Center for Health
Sciences
Reed Neurological Research Center
Los Angeles, CA 90024
Office: (213) 825-4708
Fax: (310) 206-5518

Dr. John Tangney
AFOSR/NL, Bldg. 410
Bolling AFB, DC 20332-6448
Office: (202) 767-5021
Fax: (202) 404-7475

Dr. David Tank
Biological Computation Research
Department
AT&T Bell Laboratories
Rm. 1C-427, 600 Mountain Ave.
Murray Hill, NJ 07974
Office: (908) 582-7058
Fax: (908) 582-2451

Dr. Norman Tepley
Department of Neurology, K-11
Henry Ford Hospital
2799 West Grand Blvd.
Detroit, MI 48202-2689
Office: (313) 876-1075
Fax: (313) 876-1324

Professor Don M. Tucker
Department of Psychology
University of Oregon
Eugene, OR 97403
Office: (503) 346-4963
Fax: (503) 346-4911

Dr. Harold Weinstock†
AFOSR/NE
Bldg. 410
Bolling AFB, DC 20332-6448
Office: (202) 767-4933
Fax: (202) 767-4986

Dr. John Wikswot†
Living State Physics Laboratory
Department of Physics and Astronomy
Vanderbilt University
Box 1807 Station B
Nashville, TN 37235
Office: (615) 322-2977
Fax: (615) 322-4977

Dr. Samuel J. Williamson†
Department of Physics
New York University
4 Washington Place
New York, NY 10003
Office: (212) 998-7692
Fax: (212) 995-4011

Dr. Glenn F. Wilson
AL/CFHP, Bldg. 33, Room 219
Wright-Patterson AFB, OH 45433-6573
Office: (513) 255-8748
Fax: (513) 255-8752

Dr. Chris Wood
Biophysics Group (P-6), MS M715
Los Alamos National Laboratory
Los Alamos, NM 87545
Office: (505) 665-2545
Fax: (505) 665-4507

WORKSHOP PROGRAM

MONDAY, MAY 18

- 18:30 -- 19:30 Mixer
19:30 -- 20:30 Buffet Dinner
20:30 Welcome and Introduction -- Weinstock and Fregly

TUESDAY, MAY 19

08:30 Topic 1: Theoretical and Practical Aspects of MEG and EEG -- Chair: Nunez

08:30 Wikswo Fundamental factors that affect the EEG and MEG -- information content, silent sources, spatial resolution, inward continuation, and such

09:15 Williamson Advantages of MEG

09:35 Gevins Advantages of EEG

09:55 Coffee

10:10 Sutherling Practical factors that affect the EEG and MEG -- subject preparation time, subject immobilization, artifacts, signal to noise ratio of sensors, instrument cost, technical support

10:30 Panel: Barth, Tepley, Okada, Regan, Tucker plus Topic 1 speakers

12:00 Lunch and Mid-Day Break

15:30 Topic 2: Inverse Problems -- Chair: Wikswo

15:30 Nunez. Single and multiple dipole models and inward continuation

16:00 Hamalainen New possibilities and challenges in source analysis through full-scalp magnetic coverage

16:30 Williamson Unique estimates for distributed cortical activity

17:00 Panel: Gevins, Robinson, Okada plus Topic 2 speakers

18:00 Coffee

18:15 Topic 3: Multimodality Integration -- Chair: Williamson

18:15 Coppola Integration of EEG/MEG with MRI, PET and SPECT

18:45 Wood Integration of MRI and EEG/MEG

19:15 Panel: Gevins, Lauterbur, Sutherling plus Topic 3 speakers

20:00 Dinner

WEDNESDAY, MAY 20

08:30 Topic 4: Clinical Considerations and Applications -- Chairs: Harner and Ebersole

08:30 Ebersole Practical application of source localization in partial epilepsy

09:00 Harner Clinical applications of quantitative electrophysiology

09:30 Sato Comparison of MEG and EEG in localizing epileptic foci

10:00 Coffee

10:15 Gallen Clinical applications of magnetic source imaging

10:45 Panel: Barkley, Barth, Sutherling plus Topic 4 Speakers

12:00 Lunch and Mid-Day Break

16:00 Topic 5: Perception, Cognition, and Action -- Chair: Wilson

16:00 Regan MEG and EEG in research on parallel processing in vision

16:45 Gevins Dynamic cortical networks of mental models and simple tasks

17:30 Coffee

17:45 Kaufman Differential activity of cortex: EEG, MEG, and PET as complementary modalities

18:30 Cooper How brain data help a cognitive scientist

19:15 Panel: Nakamura, Tangney, Tucker, Wood plus Topic 5 Speakers

20:15 Banquet

THURSDAY, MAY 21

08:30 Topic 6: The Future -- Chair: Weinstock

08:30 Tangney Goals and Perspectives of the Air Force

08:50 Lawrence Goals and Perspectives of the Army

09:10 Nakamura Goals and Perspectives of the NIMH

09:30 Discussion and Questions

10:00 Coffee

10:15 Copolla The Future of SPECT and PET

10:35 Lauterbur The Future of Functional MRI

10:55 Gevins The Future of EEG

11:15 Williamson The Future of MEG

11:35 General Discussion

12:00 Closing Remarks -- Weinstock and Fregly

12:15 Lunch

SCIENTIFIC INTERESTS OF ATTENDEES

- Allard:** Developing basic research programs in neuro-cognitive science for the Cognitive Science Program of the Office of Naval Research. Our goal is to develop better theories of human intelligence and information-processing capacities by understanding the multiple neural substrates of cognition. We have a special focus on high-level cognitive processes in humans and computational modeling of human cognitive architectures. Navy payoffs include improved prediction of individual differences in cognitive performance, improved human factors design, and improved instructional technologies. Current program supports work in visual cognition and memory systems. Personal research in behavioral neuroscience (human neuropsychology of speech and auditory perception and animal neurophysiology of use-dependent changes in sensory-motor representations).
- Barkley:** Gregory L. Barkley MD is the Medical Director of the Henry Ford Hospital-Oakland University Neuromagnetism Laboratory. After graduating from Michigan State University College of Human Medicine in 1981, he did his neurology residency and fellowship in clinical neurophysiology and epilepsy at Henry Ford Hospital. He is board certified by the American Board of Psychiatry and Neurology and the American Board of Clinical Neurophysiology. He is a senior staff physician in the Department of Neurology at Henry Ford Hospital and is the Director of the EEG Laboratories and the Director of the Adult Epilepsy Clinic. His research interests include the study of slowly varying neurophysiologic phenomena by DC-MEG and DC-ECOG such as spreading depression, anoxia, and epilepsy. He has also focused upon the use of DC-MEG in migraine and techniques for DC-MEG in humans. He is actively involved in clinical trials of experimental antiepileptic drugs.
- Barth:** My research is concerned with the electrophysiology of sensory information processing in animal and man, and pathological changes in the neurocircuitry of sensation produced by epilepsy. This work involves high resolution mapping of neuromagnetic and neuroelectric fields produced by populations of neurons, and numerical methods for discriminating interactions between brain regions in space and in time.
- Cooper:** Professor and Chair of Psychology Department, Columbia University Research in the area of visual cognition and perception. Specific interests in the mental representation of visual objects and events.
- Coppola:** Dr. Richard Coppola is chief of the Neuro-imaging Unit in the Clinical Brain Disorders Branch, National Institute of Mental Health Intramural Research Program located at the NIMH Neurosciences Center at St. Elizabeths, Washington, D.C. His particular research interests have involved developing and applying functional brain imaging for the study of neuropsychiatric disorders as well as gaining a better understanding of the neurophysiological substrate of normal cognition and sensory processing. The methods presently in use include

Single Photon Emission Computed Tomography and quantitative electrophysiological mapping techniques as well as Positron Emission Tomography and Magnetic Resonance Imaging.

- Ebersole: I am actively engaged in developing quantitative EEG (voltage topography) and dipole modeling of interictal potentials and ictal rhythms as new clinical tools in the evaluation of focal epilepsy. Since many of the patients we have studied ultimately require intracerebral and subdural electrodes prior to surgical therapy, we are in the fortunate position of being able to verify our predictions about the character of the cerebral generators of the signals measured at the scalp. Our goal is to be able to characterize cerebral epileptogenic sources sufficiently well by quantitative EEG analysis that the number of patients who need to undergo intracranial monitoring is minimized. I believe we have the most active clinical program of this type in the country, and I would be glad to share our experiences, data, and thoughts with the other participants. Since our data are new, not well known, and already quite extensive, I would like to be able to present them in some detail. Having also just returned from a sabbatical leave at the MEG Center in Albuquerque, I have an appreciation for the relative strengths and weaknesses of both EEG and MEG techniques, as they apply to clinical research efforts.
- Fregly: Research in cognition and electromagnetic brain activity; brain and behavior; cognitive neuroscience.
- Gevins: For the past 20 years I have been developing analytic methods, software systems and experimental paradigms for measuring the neuroelectric basis of human cognition. My approach is based on measuring the activity of rapidly shifting cortical networks as subjects perform simple but difficult cognitive tasks. Our current measurement technology includes 124-channel EEG recordings, three-dimensional finite element brain and head models derived from each subject's magnetic resonance images, correction of EEG recordings for spatial distortion due to transmission through the skull and other tissues, and computation of time-dependent correlations between evoked potentials recorded from different sites.
- Hämäläinen: I am putting together the software for a whole-head MEG system. My current interest include multidipole and continuous-distribution source modelling, realistic conductor models, and MEG-MRI integration.
- Harner: EEG analysis of epileptic force using singular value decomposition of sources, waves, spikes, & frequencies.
- Lauterbur: Magnetic resonance imaging and spectroscopy of brain structure and function.
- Lawrence: My relevant interest is to monitor developments in this area on behalf of Army Research Institute.

- Regan:
1. Visual psychophysics (motion, spatial vision, depth, binocular vision, colour)
 2. Clinic psychophysics (multiple sclerosis, parkinson's disease, amblyopia, cataract, glaucoma)
 3. Auditory psychophysics
 4. MEG & EP studies of sensory systems; vision in aviation, space & sport
- Robinson: Considerable emphasis has been placed on the use of MEG and EEG to localize components of an averaged evoked response. However, only a small fraction of the human brain is directly involved in either primary sensory or primary motor activities. I would like to discuss the role of MEG and EEG in localizing spontaneous (unaveraged) brain activity, and its potential contribution to cognitive as well as clinical science. Materials I have available for discussion include MEG measurements of epileptic discharges, single trial (unaveraged) evoked response, video of current image movies, and computer simulations.
- Sato: Application of EEG and MEG in clinical epilepsy research to localize an epileptogenic zone.
- Sutherling: The overall scientific interest and activities of the Reed-UCLA Neuromagnetism laboratory are to investigate the capabilities of dipole models applied to the extracranial magnetic and electric fields for localization and quantification of electrically active human cortex with specific applications to non-invasive presurgical localization of human partial seizures for focal excisional surgery. As a natural extension of this research, investigation of human somatosensory cortex has been performed. Comparisons are made between the non-invasive measures and invasive intracranial measures including chronically placed subdural grid electrodes and depth electrodes, with additional anatomical studies.
- Tangney: Sensory, motor and cognitive processing in biological systems. Behavioral, neural and computational approaches to these issues.
- Tepley: Norman Tepley, Professor of Physics at Oakland University and Scientific Director, Henry Ford Hospital-Oakland University Neuromagnetism Laboratory received his Ph.D. in physics from M.I.T. in 1963. His research centered on low temperature physics until 1976, when funded by the Michigan Heart Association, he began to study biomagnetism. During 1980 through 1982 he organized and initiated a non-radiological Ph.D. program in Medical Physics at Oakland University and assembled a consortium of Detroit area hospitals to participate in the research aspects of the program. In 1986, in collaboration with K.M.A. Welch, M.D., chairman of Neurology at Henry Ford Hospital, he began plans for a Neuromagnetism Laboratory. That laboratory was completed in May 1988. Since that time his research interests have focused on very slowly varying neurophysiologic phenomena which might best be studied non-invasively with DC-MEG. In addition he has worked on a variety of new techniques for the analysis of MEG and EEG data.

- Tucker: My scientific interests include neuropsychological models of emotion and psychopathology, emotional influences on attention and cognition, developmental neuroscience, quantitative analysis of scalp electrophysiology.
- Weinberg: Neurophysiology of information processing.
- Wikswo: My biomagnetic research has been directed towards using simple electrophysiological preparations and mathematical models to understand the relationship between the electric and magnetic fields associated with propagating action potentials. We have studied isolated nerves, skeletal muscle, smooth muscle, and one- and two-dimensional cardiac tissue. We have developed high resolution torodial and SQUID magnetometers to enable us to image magnetic fields and currents.
- Williamson: The direction of my research is to elucidate the relationships between macroscopic neuronal activity of the human brain and perceptual and cognitive performance. The approach is to relate magnetic source imaging (MSI) \- which establishes quantitative measures of neuronal activity at identifiable locations within the brain \- and behavioral measures on the same subjects. To this end, our laboratory at NYU has been developing neuromagnetic techniques over a period of nearly 20 years with a goal of providing a unique, quantitative characterization of the distribution of neuronal activity within the brain.
- Wilson: My scientific interests are to better understand human performance using physiological measures. In particular I am interested in human cognitive workload. I use EEG and MEG measures to gain insight into how the brain processes information when task difficulty is manipulated. I am becoming increasingly interested in multiple task environments in both the laboratory and "real world".

EVALUATION OF WORKSHOP

What is the most important concert or fact that you learned at this workshop?

- [1] The material was very new to me, so virtually everything was a learning experience. (I was quite surprised at how sophisticated EEG has become!)
- [2] There is no single best general way to image electromagnetic brain activity given the differential goals and requirements of basic and applied research and clinical situations.
- [3] It might be useful to provide an inward continuation of $\bar{B}$ up to the brain's surface.
- [4] That we need measures of local control activation, with high spatio-temporal resolution, and that correlate with other measures of local cortical metabolism and/or neuronal activity, to be used especially for studies of cognition.
- [5] No response to this question.
- [6] The EEG/MEG localization problem is under better control because fewer things are being done wrong and more of the available information, experimental and theoretical is being used. However, general solutions are still not available, and probably never will be. Worse, there is no way to tell a good approximate solution from a bad one.
- [7] Advances in functional imaging.
- [8] That there is a convergence of the capabilities of MEG and EEG. Also that the scale of the way we look at brain (point dipole $\leftrightarrow$ whole brain) can change the manner of extracting information.
- [9] Theoretical: Green's function, spatial resolution for multiple sources of MEG (power spatial Fourier Transform).
Technical: whole head, geodesic EEG electrode cap.
- [10] New thoughts concerning possible collaborations with cognitive scientists.
- [11] MEG data is being used to determine surgical procedures.
- [12] Interdisciplinary research particularly concerning cognition is a higher priority than I thought.
- [13] The workshop was a very informative conference on EEG and MEG, particularly because EEGers, MEGers, and other neuroscientists met, discussed, and exchanged information face to face. The underlying concept of not dwelling on a discussion of whether one method is superior to another, I think, led to the success of this workshop.

What is the most pressing scientific question that you leave with?

- [1] How can these methods be used to understand the nature of cognition? (Despite my remarks, I have become convinced that this is a realistic and desirable goal).
- [2] How can mechanism of brain functioning be best elucidated?
- [3] Fusion of discrete and continuous source modelling approached.
- [4] How to fully interpret EEG & MEG data.
- [5] How can we best exploit the potentially synergistic relation between MEG/EEG and functional MRI?
- [6] How to identify the most pressing scientific question. Perhaps it is how to integrate good spatial localization with good temporal resolution, so that EEG & MEG will often need to be localized only well enough to reveal which MRI/PET etc. spot is associated with which response in a sequence.
- [7] Lack of formulation specific linking hypotheses to be tested (structure-function).
- [8] Combination (or feasibility, thereof) of MEG/EEG and other neuro-"imaging" modalities is needed to advance clinical and basic scientific research on the brain.
- [9] Technical scientific questions: (1) Is it feasible to image human cortical regions with errors: center of mass 1-2 mm, area $\sim 10\%$, temporal asynchrony 1 msec? (2) Is MEG $\geq$ EEG?
Brain scientific question: What is functional anatomy of somatosensory perception?
- [10] Need for well-defined standards against which various new modelling schemes can be tested.
- [11] What level of analysis is best for cognitive work? Sources, areas, patterns of sources/areas? Technology for ECG/MEG is doing well, is time to study cognitive effects where sharp responses one finds with sensory studies do not see to occur.
- [12] Modelling sources of activity must be carefully done using a variety of techniques in order to arrive at unambiguous answers.
Whether some of the officials who review our proposals.
- [13] Complementarity between EEG and MEG was well recognized by all participants, but the application of this concept to epilepsy research is not yet conceptualized. Thus, the combination of EEG and MEG needs to be established in terms of its practical utility. This undertaking may have to be delegated to those who have both EEG and MEG capability. The news on Neuromag-122 was welcome. One group appeared to claim that MEG is a clinically useful tool, even though there is no solid evidence of such usefulness of the methodology. The application of the current density method to epilepsy research must be explored.

What points should the summary report emphasize?

- [1] Complementarity of approaches.
Notion of combining methods (EEG & MEG with PET, MRI).
Idea the cognition task analysis should make contact with EEG/MEG research.
- [2] What are the current capabilities and limitations of available brain imaging techniques and how can they be improved to impact future imaging capabilities for improving human intellectual functional in normal and abnormal work and health situations.
- [3] MEG & EEG are both useful tools for studying brain function. MEG modelling is more straightforward. Combined use is an important but largely unexplored territory.
- [4] Complexity of sources.
Need for more sensors/unit space.
Need for regular communication, workshops etc. in the EEG/MEG analysis community.
- [5] Complementarity.
- [6] Integration of EEG/MEG/MRI etc. to address well-defined fields of unique, basic or clinical. This does not have to be the "NNL" but can be done by encouraging funding agencies to ask for it and to promise money for well-concerned joint projects.
- [8] That there is a vast area of research to be done in marrying electrophysiology to cognitive science. Without cross fertilization, MEG/EEG will stagnate!
- [9] How to best improve spatiotemporal imaging of dynamic brain function.
- [10] 1. The need for better communication between the clinical researchers and the basic neuroscience researchers.
2. Questions concerning the utility of EEG and MEG for basic and clinical research require much more research (and money) to answer.
- [11] EEG-MEG complement one another and should be used together.
- [12] 1. All researchers are limited by the high costs of multichannel MEG and EEG recordings which limits our ability to do the simultaneous multichannel MEG/EEG recordings that most seem to feel are needed to resolve issues raised in the meeting. Thus more money is needed.
2. A number of attempts have been proposed to replace the ECD but none have been conclusively proven superior.
- [13] MEG is an excellent experimental tool, but it is not a clinical tool. EEG has made tremendous advances within the past decade, but needs refinement and further exploration in different areas of application, particularly of the (inward continuation) method of Gevins. This method needs to be explored to do the same thing in deeper structures of the brain, as well as superficially. The complementary nature of EEG and MEG needs to be emphasized, but the continuous exploration of EEG is as important as their relationship.

What points should the summary report not emphasize?

- [1] (I don't really understand this question...)
- [2] Controversies of any kind
- [3] Cohen's notorious paper as a starting point.
- [4] EEG vs. MEG.
- [5] The dipole argument.
- [6] The NNL
Specific hardware
EEG vs MEG
- [8] None - be frank!
- [9] Unsupported, anecdotal findings.
Findings from black-boxes which cannot be replicated/validated or understood by common scientist or common clinician.
- [10] 1. EEG versus MEG.
2. The bad rap that the current dipole received from many participants.
- [11] 1. That there is a better feud between EEG and MEG couples.
2. That ECG or MEG is absolutely the best measure for everything.
- [12] Dr. Gevins' criticism of the equivalent current dipole which differs greatly from the opinions spoken by the rest of the group.
- [13] Any statements implying that one method is better than the other should be avoided.

How might the workshop organization, food, or facilities have been improved?

- [1] It was excellent.
- [2] The addition of two or three more "Card Carrying" cognitive psychologists.
- [3] The weather could have been better on Tuesday & Wednesday!
- [4] Not easily improved!
- [5] Fine as it was.
- [6] Juice for breakfast
Avoid the uncomfortable Horizon Room

More sunshine and warmth

- [7] Fine.
- [8] Encourage more interactive panel discussions. Perhaps an agreed-to list of questions to be solved or debated might help!
- [9] More time for discussion (perhaps shorter midday break).
- [10] 1. Somewhat more time for one-on-one conversation.
2. Otherwise - very good job! Thank you.
- [11] Include a group picture to avoid numerous flashes, clicks and whiring(sic) noises during the meeting!! Facilities, food, etc. were great - well done, timer was good idea.
- [12] 1. The breakfasts had too much fat - sausages, bacon, hash brown etc., I would emphasize juice, fruits, cereals etc. Also better wines with dinners would be nice.
2. The meeting was well organized and the time keeper did as good job of keeping on track. Discussions were fruitful.
- [13] The workshop was well organized and the participants were well fed.

WHAT NEW CHIPS OFF OLD BLOCKS?

*When researchers stop counting to ten,
And the patients start smiling again,
And all brain functions known,
Thanks new seeds here were sewn,
Will John Wikswo at last say, "Amen"?*

*Will the brain models left to compose
Prompt such poetry rather than prose,
And when all's done and said,
Will a brain that's well read
Make it clear that we smell like a rose?*

*Will the cognitive types jeer or cheer,
Or be doomed to still cry in their beer,
When techniques we behold
Are more bold and best told
Without dipoles provoking their fear?*

*Will John Tangney feel much more at ease
At less things that have caused him to sneeze,
And will Weinstock be pleased
That news skids were well greased
Or, like some, still be wailing "Aw geez"?*

*And will Alan and Sam, Lloyd and Chris
Always tell us their research can't miss,
If our faith is ne'er lost,
At whatever the cost,
For our mutual sharing of bliss?*

*And will Sutherling/Sato/Okada
Be satisfied soon, as they oughta,
If Paul Lauterbur's stuff
Shows them more than enough,
And all clinical types join with "Uh huh"?*

-Al Fregly, Prog. Mgr., AFOSR (Ret.)

REPORT OF EXPENDITURES

Salaries & Benefits:

Office Clerical Wages	\$1,507.88

Total Salaries & Wages	\$1,507.88
FICA	115.36
Health Insurance	196.65
Group Life Insurance	5.45
Disability Insurance	7.11
Other Fringes	0.00

Total Benefits	\$324.57

Total Salaries & Benefits	\$1,832.45

General Supplies:

Duplication	0.00
Postage	188.53
Office Supplies	798.46
Lab Supplies	59.00
Telephone - Long Distance	0.00
Meetings Expense	6,173.55
Rental of Equipment	1.55

Total General Supplies	\$7,221.09

Travel Expense:

Travel Faculty	4,579.98
Travel Students	852.45
Travel Other	2,466.03

Total Travel Expense	\$7,898.46

Total Supplies & Travel	\$15,119.55
-------------------------	-------------

Total Expenses	\$16,952.00
----------------	-------------

Grant Total	\$16,952.00
-------------	-------------

Total Unspent Balance	\$0.00
-----------------------	--------