SYNCHRONOUS BRAIN EVOKED POTENTIAL CORRELATES OF
DIRECTED ATTENTION IN HUMANS

by

THOMAS FRANCIS COLLURA

Submitted in partial fulfillment of the requirements
for the Degree of Doctor of Philosophy

Department of Biomedical Engineering
CASE WESTERN RESERVE UNIVERSITY
TO MY
Howard
SYNCHRONOUS BRAIN EVOKED DIRECTION ATTENTION

Abstract

THOMAS FRANKLIN

Synchronous filtering of EEG sensitive new tool for the study of brain processes; through a multiple-channel system, several different brain centers can be monitored in parallel and individually from a single electrode location.

In these studies, the relationship between evoked potentials and selective attention in subjects who voluntarily control their behavior in a difficult sensory task is studied. Evoked potential records provide information about attention, general arousal, and other brain processes to be effectively monitored.
ACKNOWLEDGEMENTS

I would like to thank Leon D. Harmon and Ronald J. Lorig for serving as research advisors during this study, for serving on the committee, and for providing laboratory facilities and equipment.

I would also like to thank Dov Hazony and James L. Mack for serving on the committee.

I would like to thank Wes Heisey for the use of the sound-pressure-level meter, and Phil Wagner for the use of the thermopile and electrometer.

I owe my final thanks to my wife and daughter for their continued patience and encouragement.

This work was supported by the National Institutes of Health under Training Grant GM-01090.
# TABLE OF CONTENTS

<table>
<thead>
<tr>
<th>Chapter</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td><strong>INTRODUCTION</strong></td>
<td>1</td>
</tr>
<tr>
<td></td>
<td><strong>CHAPTER 1 - EVOKED POTENTIALS</strong></td>
<td></td>
</tr>
<tr>
<td>1.1</td>
<td>Anatomy &amp; Physiology</td>
<td>3</td>
</tr>
<tr>
<td>1.2</td>
<td>Signal Characteristics</td>
<td>5</td>
</tr>
<tr>
<td>1.3</td>
<td>Overall Model</td>
<td>8</td>
</tr>
<tr>
<td></td>
<td><strong>CHAPTER 2 - ATTENTION AND EVOKED POTENTIALS</strong></td>
<td></td>
</tr>
<tr>
<td>2.1</td>
<td>Evoked Potentials in Sensory Psychophysics</td>
<td>18</td>
</tr>
<tr>
<td>2.2</td>
<td>Experimentation for EP's and Attention</td>
<td>20</td>
</tr>
<tr>
<td>2.3</td>
<td>The Experimental Design</td>
<td>23</td>
</tr>
<tr>
<td></td>
<td><strong>CHAPTER 3 - THE SYNCHRONOUS EVOKED POTENTIAL MEASUREMENT</strong></td>
<td>28</td>
</tr>
<tr>
<td></td>
<td><strong>CHAPTER 4 - INSTRUMENTATION AND MEASUREMENT</strong></td>
<td>32</td>
</tr>
<tr>
<td></td>
<td><strong>CHAPTER 5 - EXPERIMENTAL RESULTS</strong></td>
<td></td>
</tr>
<tr>
<td>5.1</td>
<td>Statistical Procedures</td>
<td>35</td>
</tr>
<tr>
<td>5.2</td>
<td>Findings</td>
<td>42</td>
</tr>
<tr>
<td>5.3</td>
<td>Summary and Recapitulation</td>
<td>53</td>
</tr>
<tr>
<td></td>
<td><strong>BIBLIOGRAPHY</strong></td>
<td>56</td>
</tr>
</tbody>
</table>
INTRODUCTION

The electroencephalogram (EEG) as measured from the intact human scalp is of interest in psychology and psychophysics because it can provide an indication of the activity of brain cells in the awake, alert state. Of particular use are the minute potentials evoked by sensory stimuli, for these time-locked transient wavelets show how populations of cells behave in response to afferent volleys carried by primary sensory fibers.

Sensory evoked potentials are difficult to measure because they represent the activity of only a small portion of the cells producing surface potentials, and are thus buried in background EEG "noise". Some form of signal-to-noise improvement is therefore necessary, and this implies a time delay for the gathering and processing of a large number of noisy responses in order to provide an evoked potential estimate in which the noise level has been reduced.

Evoked potentials are generally measured by averaging, and this requires one to two minutes for the acquisition of a single wave estimate. Since ongoing brain processes may
produce evoked potential changes in mere seconds, averaging does not provide a suitable means of studying dynamic changes in brain activity. Synchronous filtering has the capability for rapid and ongoing measurement of evoked activity, and can respond accurately to show changes occurring over periods as short as five seconds.

With this capability at hand, the purpose of this study is to identify and characterize short-term changes in evoked potentials which are associated with the voluntary direction of attention toward visual or auditory stimuli. An alert subject is given the task of detecting and signaling small changes in the intensity of light or sound stimuli, and visual and auditory evoked potentials are studied as a function of which modality is the subject of attention. The interpretation of results will take two forms: finding systematic relationships between evoked potential measurements and task variables within and across subjects, and identifying signatures, similarities, or classifications which suggest themselves in the data. The results reported here permit an improved characterization of the short-term processes underlying the control of directed attention in normal human subjects.
CHAPTER 1

EVOKED POTENTIALS

1.1: Anatomy & Physiology

The cellular origin of the EEG has been the subject of a great deal of research during the last twenty years. Elul (1972) and Creutzfeldt (1975) provide complete and authoritative discussions of the significant results, ar this material forms the basis for the model described here.

When muscle and eye movements are minimized by relaxatio the predominant sources of scalp potential are populatio of cells in the brain, with large cortical cells providi the majority of the voltage. Due to the distribution of ions across active membranes, each cell tends to take on dipole characteristics and produce potentials which are carried to the scalp by volume conduction (Mountcastle 1974). When cells polarize in asynchrony, the net surfa potential is small due to the cancellation of out-of-phas components. The presence of a measurable surface poten tial thus depends on the fact that some cells are polar-
izing in synchrony, generally in response to an afferent volley in which fibers are firing in unison.

When a single brief stimulus is presented to the nervous system, the response generally consists of a single time-limited pattern, or burst, of action potentials carried along the appropriate afferent pathway. In the case of a light flash, the optic nerve carries the impulses; in the case of a click, the auditory nerve is involved. In both cases, sensory fibers first synapse at lower brain centers; second, third, and higher-order fibers then carry a volley of processed information to the appropriate sensory cortex. The cortical response in both modalities consists of a time-limited sequence of processing steps involving various areas of the brain; there is a substantial amount of information exchange or "crosstalk" between cortical centers, with pathways including lower brain areas. A sufficient number of cells are involved in these processes to give rise to measurable transient surface waves, the evoked potentials. Some evoked potential waves appear to involve predominantly localized cortical areas, others result from activity over widespread locations.

The duration of a typical visual or auditory evoked potential does not exceed 1 second, and only the early part,
which comprises the first 250 milliseconds, is consistently repeatable (Dustman and Beck 1963, Ellingson et al. 1972). The later parts may vary considerably with subjects from moment to moment, and have been found to depend strongly on stimulus meaning, uncertainty, and other interpretive factors (Chapman et al. 1974, Johnston & Chesney 1974).

For the purposes of this study, only the primary (first 250 milliseconds) evoked potential is of interest. This is because at the stimulus rates employed (>3 per sec), the later parts disappear (van Hof 1960, Sato et al.). By combining repetitive stimulation with synchronous presentation, it becomes possible to monitor the changing of the evoked wavelets over time periods as short as five seconds, as limited by the filter response time-constant.

1.2: Signal Characteristics

The 250-msec primary visual and auditory evoked potentials (vep, aep) can be further broken down into two components which will be denoted as vep 1 and vep 2 for the visual and aep 1 and aep 2 for the auditory. These two components have been recognized by other workers based on their signal characteristics, but their functional significance...
which will be described here, has been unclear (Davis 1973, McGillem & Aunon 1977a,b).

The basis of the two-part model is the observation that evoked potentials have a low-frequency (below 8 Hz) and a high-frequency (above 14 Hz) part. The breakdown is readily evident from inspection of power- or amplitude-spectra computed from averaged evoked potentials, and is shown graphically in Figure 1. The component $e_{p1}$ consists of a single diphasic wavelet with duration of about 200 msec; its amplitude spectrum thus centers at approximately 5 Hz. The component $e_{p2}$ completes three cycles in about 200 msec, and its amplitude spectrum centers between 15 and 20 Hz. Since energy is additive in both the time and frequency domains, we have:

$$e_{p} = e_{p1} + e_{p2}$$  \hspace{1cm} (1)

$$S_{e_{p}} = S_{e_{p1}} + S_{e_{p2}}$$  \hspace{1cm} (2)

in which $e_{p}(t)$ is a single evoked potential wavelet, and $S_{e_{p}}(f)$ is the power spectrum of $e_{p}(t)$.

Davis (1973) was the first to report this systematic breakdown as found from power spectra, and employed multielectrode recording to elucidate the topographic
FIGURE 1
details of the two components. In both the visual and auditory modalities, the component ep 2 is greatest in the primary projection area of the relevant modality, and ep 1 is measured diffusely, with significant voltage covering most of the scalp, centered at the temporal and vertex areas.

1.3: Overall Model

A variety of evidence will now be brought to bear on the functional relationship between the ep 1 and ep 2 components, and to clarify their anatomical and physiological substrates. Let it first be noted that the relatively short latency of the first peak of ep 2, the short latencies of the subsequent peaks, and the observation that ep 2 is greatest over the primary sensory cortex strongly suggest that ep 2 is produced by the initial primary sensory cortical activity, and the resultant fast communication between layers and areas, perhaps involving parts of association cortex. It must also be recognized that activity with lower brain centers may be involved, in much the same way that recurrent volleying between cortex and thalamus gives rise to the spontaneous alpha wave (Andersen and Andersson 1975).
Based on the longer latency and diphasic shape of ep 1, it can be argued that this component represents later, diffuse brain activity in response to the stimulus, in which wide-spread areas of the cortex respond with latencies ranging from 30 to 150 msec. Of paramount importance here is the independence of the ep 1 and ep 2 components. If they represent merely different harmonic representations of the same process, little is to be gained by taking the trouble to study them individually. It has been observed, however (Trehub 1965, Collura 1976), and will be seen here, that the two behave independently and represent distinct brain processes.

The most compelling evidence is based on lesion studies involving acute cerebral trauma in humans. Greenberg et al. (1977) studied evoked potentials in 51 patients with head injuries, and created a systematic description of the evoked potential changes resulting from injury to various cortical areas. They classified averaged evoked potentials according to the presence or absence of wave peaks and arrived at four classes which they named Grades I through IV. Grade I is normal and Grade IV is electrical silence. Grade II is characterized by several peaks of short latency, and corresponds with the condition ep 1 absent. Grade III consists of a single longer-latency
peak and corresponds to the condition ep 2 absent.
The grades were formed without apparent knowledge of
the ep 1 - ep 2 breakdown, and were based on the most
useful classification of the results of the lesion studies.

The interpretation of the results of Greenberg et. al.
(1977) requires an understanding of the anatomical path-
ways involved. Only the visual system will be covered in
any detail, for two reasons. First, in the experiments
which follow, only the visual evoked potentials provide
significant results. Second, the lesion studies provide
little insight into the auditory system, due to the fact
that the primary projection is in close proximity to
other cortical areas, while the primary visual cortex
is located occipitally, well away from the other cortical
areas of interest.

Figure 2 provides a graphical summary of the important
pathways of the afferent visual system, based on the
descriptions given by Mountcastle (1974) and Guyton (1971).
The important point to note is that the precortical path-
ways include two major subcortical systems: one which
synapses at the lateral geniculate nucleus and projects
to area 17 (primary visual cortex), and a second system
which synapses at the superior colliculus and projects
via the thalamus to the prestriate and inferotemporal
areas 18, 19, 20, and 21. It is apparent from Figure 2 that knowledge of the cortical distributions of vep 1 and vep 2 does not suffice to define the anatomical basis of their functional independence. For example, the component vep 1 could be produced by a spreading of activity from area 17, or by systems originating cortically in areas 20 and 21. The lesion studies serve to clarify these matters as follows:

Greenberg et al. (1977) classified visual and auditory evoked potentials obtained from neurosurgical patients who had had severe cerebral trauma involving functional and anatomical loss of specific cortical areas. Their results are summarized in Table I, along with the interpretation of these results in terms of the ep 1 - ep 2 model. The significant facts to be drawn from this table are as follows:

1) The frontal lobes are not essential to the complete appearance of ep components.

2) The parietal lobes are essential to the appearance of vep 1, but not vep 2.

3) The temporal lobes are essential to the appearance of vep 1 and the entire aep, but not vep 2.

4) The occipital lobes are essential to the appearance of vep 2, but not vep 1.
**TABLE I**

**RESULTS OF LESION STUDIES**

(Greenberg et al. J Neurosurg. 47:150-177, 1977)

<table>
<thead>
<tr>
<th>LESION</th>
<th>CLASS (other than I)</th>
<th>EVOKED POTENTIAL CHANGES</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frontal</td>
<td></td>
<td>None</td>
</tr>
<tr>
<td>Parietal</td>
<td>II VEP</td>
<td>vep 1 disappears</td>
</tr>
<tr>
<td>Temporal</td>
<td>II VEP IV AEP</td>
<td>vep 1 disappears aep 1 and 2 disappear</td>
</tr>
<tr>
<td>Occipital</td>
<td>III VEP</td>
<td>vep 2 disappears</td>
</tr>
</tbody>
</table>
These facts can be combined to yield an anatomical basis for a model such as shown in Figure 3. Based on the knowledge that information enters via a single channel and at some time appears in two independent systems, the minimal model must include an input, decussation, two parallel mechanisms, and possible activity later in the system. Figure 4 shows the relevant anatomy in better detail than Figure 2, along with markings indicating the corresponding elements from Figure 3 based on the results of the lesion studies.

This elucidation of the anatomical foundation of the vep 1 - vep 2 distinction has particular significance for psychophysics because the two systems thus separated have quite different functions in the human brain. The vep 2 system is that conventionally regarded as "the afferent visual system", and gives rise to perception and conscious awareness including feature detection. The basis for this point of view is the ubiquitous clinical finding that loss of area 17 leads to irreversible blindness. The vep 1 system covers brain centers involved with eye movements, eye-hand coordination, and other automatic processes not generally associated with conscious, volitional control. Indeed, patients who are blind owing to loss of area 17 but whose remaining cortex and brain are intact may be observed to have unconscious, auto-
matic reactions to flashing lights or moving objects; patients with localized blind spots, or scotomata, resulting from small lesions of area 17, may unconsciously track lights presented in the blind spots (Lewin 1978).

The two components vep 1 and vep 2 thus represent the two basic functional systems underlying visual information processing. By measuring them in parallel and in real time, it becomes possible to track both the conscious and unconscious mechanisms handling visual input, and describe with some accuracy the predominant trends in the flow of information related to the experimental stimuli.

This characterization emphasizes the unsuitability of peak-to-peak measurements for accurately revealing changes in brain responsivity; a single peak-to-peak measurement generally includes contributions from both the vep 1 and vep 2 components, and waves with latencies above 250 msec include other components as well. The most advantageous means to study the components is to make best use of their different spectral characteristics, i.e. distributions of dominant energy. This is discussed in Chapter 3.
2.1: Evoked Potentials in Sensory Psychophysics

With the introduction of computer-based evoked potential averaging, it became possible to study noise-free responses to sensory stimuli, and a great deal of interest was directed toward finding systematic relationships between electrophysiological measurements and psychophysical variables. A distinct literature has appeared treating the relationships between averaged evoked potentials and various types of attention (cf. Karlin 1970, Tecce 1970, Naatanen 1974).

While a number of investigators report positive findings (Spong et al. 1965, Garcia-Austt 1968, Isgur & Trehub 1973, Schechter and Buchsbaum 1973), it must be concluded that no experiments have statistically demonstrated evoked potential dependence on modality-specific, selective attention in individual subjects. Reported results do not justify claims, either for procedural or analytic reasons.
A significant amount of confusion stems from the general use of peak-to-peak measurements in characterizing responses. Since the various peaks and troughs represent mixtures of the ep 1, ep 2, and later components, it is commonly found that some measurements react unsystematically to experimental variables (Ciganek 1975).

Limitations in experimental design which result from the requirements of response averaging produce difficulties in the interpretation of many results. If multimodality evoked responses are used, stimuli must alternate in some fashion. Since the subject may make determinations about the temporal sequence of relevant and irrelevant stimuli, moment-to-moment changes in general arousal or alertness may be disguised as the results of selective attention (Karlin 1970). The experimental precautions required to obviate this problem have led to complicated procedures which confound the formation of conclusions.

The analysis of experimental results has been compromised in many studies due to inadequate statistical procedures. The dedicated computer of average transients lacks the capability for measurement of response variance, so many results are based on visual comparison of averaged evoked potential traces; the reader is left to base conclusions on the published "selected" data. Other investigators
present data averaged over populations of subjects, obscuring individual differences and trends (Spong et al. 1965, Schechter & Buchsbaum 1973).

At the core of the analytical problem is the fact that an averager-based system takes a relatively long time (1 to 2 minutes) for a relatively small amount of information (a single wave estimate of the average evoked activity). In this regard, it should be noted that faster computer-based procedures (McGillem & Aunon 1976) offer promise in the study of these and other short-time processes. However, the synchronous filtering method applied here provides greatly reduced cost and comple...

2.2: Experimentation for Evoked Potentials and Attention

The design of an experimental study of the effects of attention on evoked activity requires a definition of the relevant functional characteristics. In the present study, interest is directed toward inter-modality selective auditory and visual attention toward the intense stimuli with no verbal or semantic meaning. It is as if that attention is directed toward stimuli in a given modality if, over a specified interval, the subject reliably makes accurate judgements in a difficult intensity discrimination task in that modality. This paradigm
been applied by previous researchers (Geisler 1960, Spong et al. 1965, Garcia-Austt et al. 1968, Gardiner & Walter 1968) and has met with varying degrees of success. Most studies indicate that an easy, routine discrimination does not produce discernible changes in evoked activity, while a difficult task generally does.

With regard to detailed model characteristics, it is important to refrain from hypothesizing the existence of distinct attentive mechanisms comprising "filters", "discriminators", or "relevance computers". As Neisser (1976) has pointed out, such modeling efforts are unnecessary and have, historically, met with little success. Any multichannel, variable capacity processor may exhibit behavior describable as selective processing, but this does not imply that a well-defined anatomical or functional subset can be found which gives rise to this characteristic alone. Selective attention may, presumably, produce simple quantitative changes in evoked activity, and such changes can be expected to indicate relative processing and processing interdependence, but no sensory or perceptual valve need be sought anywhere in the nervous system.

The specification of inter-modality selective attention allows the experimental designer to take advantage of pairing and counterbalancing to separate specific from
non-specific effects, and modality-specific from time-dependent effects. That is, the task can be arranged in such a way that the data analysis readily separates selective attention from overall attention or arousal, and allows each factor to be evaluated quantitatively (Plutchik 1968).

The experiment used in this study was designed to satisfy the following requirements:

1) At all times during which data are taken, both auditory and visual stimuli are continually presented; no systematic changes occur in the stimuli between the paired conditions.

2) At all times during which data are taken, the subject is demonstrably engaged in a difficult discrimination task, and performing well.

3) There are no systematic differences between the paired task conditions with regard to external conditions, mental set, overall arousal level, or task difficulty.

4) The subject must not be able to judge or predict changes in the likelihood of a relevant stimulus or target on a moment-to-moment basis.

5) The experiment must be properly paired and counterbalanced, and should be brief to minimize the effects of boredom or fatigue.

The objective of the data handling is twofold: to identify and compute the statistical significance of task-related evoked activity, and to seek individual characteristics and assess their potential importance as indicators of