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A TOPOGRAPHIC STUDY OF CORTICAL POTENTIALS
ASSOCIATED WITH SACCADIC EYE MOVEMENT.

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**A TOPOGRAPHIC STUDY OF
CORTICAL POTENTIALS ASSOCIATED WITH SACCADIC EYE MOVEMENT**

by

DIANE KURTZBERG

**A dissertation submitted to the Graduate
Faculty in Psychology in partial fulfillment
of the requirements for the degree of Doctor
of Philosophy, The City University of New York.**

1973

This manuscript has been read and accepted for the Graduate Faculty in Psychology in satisfaction of the dissertation requirement for the degree of Doctor of Philosophy.

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To B.G.

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ABSTRACT

A TOPOGRAPHIC STUDY OF
CORTICAL POTENTIALS ASSOCIATED WITH SACCADIC EYE MOVEMENT

by

Diane Kurtzberg

Advisor: Dr. Lloyd Gilden

Through the averaging of scalp-recorded potentials time-locked to voluntary saccadic eye movements in man, electrocortical activity both preceding and following the eye movements was identified. Activity preceding saccades was designated as the "antecedent potentials", and activity which followed the eye movements as the "lambda response". The scalp distribution of the antecedent potentials revealed areas of maximal activity in the parieto-occipital and the posterior frontal regions, which overlie the classical cortical eye fields defined through stimulation studies. The functional significance of these potentials, based upon their scalp distribution and time course, was discussed. The antecedent potentials might reflect in part the neural activity concerned with the motor command, the corollary discharge, and preparation for the subsequent saccade. The theoretical and empirical basis for these proposals was discussed.

The lambda response, which followed eye movements over a patterned field, was revealed to have a distribution

limited to the occipital region. The VER to shifts of the same pattern disclosed not only similar morphological and temporal characteristics, but a comparable scalp distribution as well. Both responses were altered by a reduction in field luminance by increased latency and decreased amplitude. Based upon these findings, which confirm observations by others, the lambda response was thought to be an evoked response due to the change in retinal stimulation at the onset of the saccade.

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CHAPTER I
INTRODUCTION

For the visual system to resolve an image with maximum precision, the object of regard must be projected onto the fovea. This is most often accomplished by rapid shifts of eye position which occur in normal vision at the rate of two to four times a second. In addition to these "saccadic" eye movements, the visuomotor system is capable of smoothly tracking steadily moving objects as well as adjusting ocular vergence to sustain binocular fixation at varying object distances. Each of these ocular movements is thought to be subserved by distinct neuronal systems involving both cortical and subcortical structures (Robinson, 1972). This study is concerned with an assessment of cortical involvement in the saccadic eye movement system as manifested by scalp recorded average brain potentials in human subjects.

Evidence for cerebral involvement in the mechanisms underlying eye movement control first appeared in clinical reports of oculomotor dysfunction following cerebral injury (Andral, 1834). Clinical studies have implicated both frontal and posterior cortical areas in the control of eye movements (Holmes, 1921; Meyers, 1931; Crosby, 1953).

Patients with unilateral frontal lobe lesions display paralysis of conjugate gaze in the contralateral direction and deviation of the eyes toward the side of the lesion, often associated with head deviation and contralateral hemiplegia. Although lesions of the parieto-occipital area are most prominently manifested by visual field defects, there are, in addition, oculomotor disturbances including conjugate deviation, fixation difficulties, and disruption of optokinetic nystagmus.

Experimental approaches to define the neural mechanisms which underlie oculomotor functioning have utilized three techniques: electrical brain stimulation (Fritsch and Hitzig, 1870); selective cortical ablation (Ferrier and Yeo, 1884); and recording of brain potentials, including EEG (Evans, 1952), averaged cerebral potentials (Remond, Lesevre, and Torres, 1965) and neural unit recordings (Bizzi, 1967).

1. Electrical Stimulation

a. Studies in Experimental Animals:

The success of Fritsch and Hitzig (1870) in eliciting movements by electrical stimulation of the brain, prompted many investigations utilizing this technique to delineate the motor areas of the brain. Early reports of ocular movements obtained in this manner were part of this quest. Two cortical areas, in the frontal and parieto-occipital regions, were found to elicit ocular responses through electrical stimulation.

(1) Frontal Eye Field (FEF):

In 1874, Ferrier reported the results of electrical stimulation of the frontal region of a lightly anesthetized monkey. He found the area from which eye movements could be elicited to be in the middle frontal gyrus. Stimulation of one side elicited eye and head movements to the contralateral side, as well as elevation of the eyebrows and eyelids and pupillary dilation. Subsequent investigations in various species of monkeys and apes replicated these findings, but found the responsive areas to be slightly more widespread (Schaefer, 1888a; Horsley and Schaefer, 1888; Beevor and Horsley, 1888; Leyton and Sherrington, 1917).

Supplementing the observations of these earlier workers, Crosby, Yoss, and Henderson (1952) stimulated the FEF in the monkey and found a pattern of localization of eye movements which included a mirror-image duplication within the convexity just anterior to the arcuate sulcus. The authors speculated that this duplication was associated with a dual mechanism of suppression and facilitation of the musculature which produces conjugate eye movements in various planes.

(2) Parieto-Occipital Eye Field (PEF):

Ferrier also obtained eye movements upon electrical stimulation of the angular gyrus in the monkey. These movements were conjugate to the opposite side and were associated with closure of the lids and pupillary

contraction. An upward deflection of the eyes was obtained with stimulation of the anterior limb of the angular gyrus, and a downward deflection with posterior limb stimulation. He obtained no eye movements with occipital lobe stimulation.

As reported in a review by Rabagliati (1878), Luciani and Tamburini noted conjugate deviation to the opposite side without any constant upward and downward inclination with stimulation of the angular gyrus in dogs and monkeys. Stimulation of the convexity of the occipital lobe elicited similar, but smaller movements.

Schaefer (1888a) reported that excitation of the posterior limb of the angular gyrus, the upper end of the middle temporal gyrus and of the whole of the occipital lobe produced conjugate deviation of the eyes. In addition, he divided the areas into three zones: 1) an upper zone, which produced a lateral eye movement accompanied by a downward inclination; 2) a lower zone, associated with lateral and upward deviation of the eyes; and 3) an intermediate zone, accompanied by a purely lateral movement. Schaefer considered these eye movements to represent a visual fixation response to subjective sensation caused by stimulation of the visual cortex. This led him to postulate connections between this area of cortex and the retina. Walker and Weaver (1940) stimulated points of the occipital lobe of the monkey under light anesthesia and obtained essentially the same results as Schaefer. They reported response latencies at one to two seconds and found the

strength of stimulus required to produce eye movements to be consistently higher than for stimulation of the FEF. Points close to the external calcarine fissure possessed lower thresholds than those near the margin of the striate cortex. The parastriate area had a still higher threshold.

Crosby and colleagues (Crosby and Henderson, 1948; Henderson, 1949; Crosby, 1953) also stimulated areas 17 and 18 in the monkey, confirming the findings of Walker and Weaver. In addition, they found that stimulation of area 19 reversed the vertical direction of the movements; that is, points in the upper portion of area 19 elicited upward contralateral eye movements; stimulation of the lower half produced a downward deflection of the eyes.

Stimulation of the inferior parietal lobule (area 7) in the monkey also produced conjugate deviation of the eyes (Fleming and Crosby, 1955). These excitable points were located at the junction of the intraparietal and superior temporal sulci extending ventrally along the intraparietal sulcus. Topographically, the deflections had an upward component at the junction and a downward component further centrally.

Several of the early investigators observed the effects of bilateral cortical stimulation in monkeys. Schaefer (1888a) found a "struggle between the muscles" responsible for lateral movement, causing the eyes to quiver back and forth without gross lateral movements. At times, one set of muscles overpowered the other and a lateral movement would result. Mott

and Schaefer (1890) bilaterally stimulated two homologous points of the frontal cortex, which produced fixation of the visual axes on a distant object. This suggested that both hemispheres are active in visual fixation and indeed perhaps in conjugate movements as well. Sherrington (1893) repeated this experiment in two monkeys in which the right and left oculomotor and trochlear cranial nerves were sectioned, leaving only the abducens nerves, innervating the external recti, intact. The result of bilateral excitation of the frontal cortex was "to cause both eyes to be rotated inwards up to, and certainly in some trials, beyond the primary position." Sherrington concluded that convergence must have been due to simultaneous bilateral inhibition of the tonus of the right and left external recti.

Mott and Schaefer (1890) placed one electrode on a point within the frontal area of the monkey which caused a lateral movement in one direction, and a second electrode on a point in the occipital area which elicited a movement in the opposite direction. When these two points were simultaneously stimulated, a lateral deviation away from the frontal site occurred, as if the frontal cortex alone were stimulated. This finding is consistent with Schaefer's (1888b) comparison of eye movement latency in response to stimulation of the frontal and posterior eye fields. The latency was longer by "some hundredths of a second" with occipital area stimulation. Schaefer hypothesized that nervous impulses arising from the posterior region must go

through at least one more nerve center than the other. He eliminated the frontal lobe as the mediating center, when after its complete excision, eye movements were still obtainable with occipital lobe stimulation.

More recently, Robinson and Fuchs (1971) noted that electrical stimulation of the visual cortex in the monkey elicited saccadic eye movements at a latency of 70 msec as compared to a latency of 25 msec with FEF stimulation. This latency is substantially shorter than reported by earlier investigators, presumably reflecting more effective stimulating and recording techniques.

The early workers were vague in their descriptions of the level of anesthesia under which the animals were stimulated. The effect of varying the state of consciousness on electrically produced eye movements was specifically studied by Krieger, Wagman, and Bender (1958). They concluded that the excitable cortical area was greater in the alert preparation and that the response from a cerebral point may change as the level of arousal varied. Subsequently, Wagman (1964) electrically stimulated the cortex of unanesthetized, cervically transected monkeys and reported more widespread responsive areas than had previously been found. These included the entire occipital lobe, a large portion of the frontal lobe and portions of the parietal lobe. The only areas not producing eye movements upon stimulation were on either side of the central sulcus. The temporal lobe was not studied. Wagman stimulated each

point on the cortex with increasing intensity until a reproducible ocular response occurred. Threshold intensity for each point was not specified; neither were the latencies nor the type of eye movement reported. In the absence of these data, firm conclusions cannot be reached regarding the extent of cortical representation of oculomotor control.

The stimulation study of Robinson and Fuchs (1969) satisfies the foregoing stringent, but essential, requirements for assessing the role of the FEF in the initiation of saccadic eye movements. Using brief intracortical pulse trains in unanesthetized monkeys, single contralateral saccades were elicited from FEF stimulation, usually at a latency of 25 msec. With stronger stimulation, the latency was reduced to 15 msec. The shortest latency between third nerve stimulation and eye movement is 5 msec (Robinson, 1968), thus leaving 10 msec for transmission from cortex to oculomotor neurons. This suggested to Robinson and Fuchs that the FEF are closely coupled to the oculomotor nuclei, although direct synaptic connections have not been anatomically demonstrated. In addition to latency measurements, they described the amplitude and direction of saccades elicited by stimulation of specific regions within the FEF. Four discrete cortical regions, each producing specific saccades were found:

1. Anterior to the posterior angle of the arcuate sulcus: small (1-5°) horizontal saccades.

2. Between the superior limb of the arcuate sulcus and the posterior tip of the principal sulcus: medium-sized

horizontal saccades (5-15°).

3. Small area (3-4 mm in diameter) in the buried cortex within region 2: saccades with large up or down components.

4. Anterior to 2 beneath the upper ramus of the arcuate sulcus: threshold was high (1-2 ma) and saccades were large (20-60°), horizontal, and of long latency 50-100 msec.

The least current required to evoke an eye movement to every stimulus (threshold) varied with location on cortex. The most sensitive region was in and near the gray matter between the principal and arcuate sulci where thresholds were between 0.1-0.5 ma. As stimulation was moved out around this area, thresholds increased. The results of Robinson and Fuchs suggest a close functional relationship between the FEF and the initiation of eye movement. This study has important implications for the interpretation of studies which have recorded electrical activity associated with eye movement (see Section 3b).

b. Human Studies:

In man, Bechterew (1899) was the first to report conjugate eye movements to the opposite side elicited by electrical stimulation of the caudal part of the middle frontal gyrus. Later, Foerster (1931, 1936) found areas from which eye movements could be elicited at the foot of the middle frontal gyrus (area 8 α,β,δ) and superior to this near the midline (area 6 α,β). The latter area produced

movements of the head and trunk along with eye movements. Penfield and Boldrey (1937) elicited conjugate deviation of the eyes alone to the contralateral side with stimulation of regions which included frontal areas 8 and $6\alpha, \beta$; as well as posterior sites within areas 19; 5α , 7β . They did not find adverse movements of the head and eyes together from area $6\alpha, \beta$ excitation, as did Foerster.

Rasmussen and Penfield (1948), stimulating the frontal cortex in man, found one-third of the points from which eye movements were elicited to be located immediately anterior to the central sulcus (area 4 and caudal portion of area 6); one-fifth of the points were found in the anterior half of the precentral gyrus (area 6). The remaining points (about one-half) were situated in the caudal portion of the adjacent frontal convolutions, mainly in the vicinity of the middle frontal convolution (area 8). Lemmen, Davis, and Radnor (1959) stimulated the area rostral to premotor area (areas 8 and 9) and reported two strips with a topographic pattern that was consistent with repeated stimulation. In the more posterior of these regions, from above downward, stimulation evoked a contralateral and downward conjugate deviation of the eyes; horizontal conjugate gaze to the other side; contralateral conjugate oblique upward deviation; and at the lower margins, divergence of the eyes. On the gyri rostral to this area, horizontal conjugate gaze to the opposite side and divergence of the eyes were elicited.

c. Conclusions from Studies of Electrical Stimulation:

Electrical stimulation of cortex in man and monkey has disclosed two regions within the frontal and parieto-occipital areas from which conjugate eye movements are elicited. There are differences in the extent and direction of ocular movement elicited within these regions in different investigations. These discrepancies are probably due in most cases to variations in experimental methods, including parameters of stimulation and level of anesthesia. For example, in his clinical studies, Foerster elicited both eye and head movements from the same cortical sites from which Penfield and coworkers elicited only ocular movements. Penfield attributed this to the use of a stronger stimulus intensity by Foerster which he believed evoked an epileptic afterdischarge. Another problem is that a strong enough stimulus may elicit eye movements from widespread areas of cortex, as in Wagman's experiments, due to the spread of current to more circumscribed lower threshold regions as delineated by Robinson and Fuchs in the frontal cortex.

In most reports, neither latency, threshold, nor the dynamic characteristics of the eye movement (i.e., amplitude and velocity) were specifically reported, making it difficult to compare the results of different investigations. This deficiency is especially important in those experiments employing anesthetic agents, as these are known to produce

changes in the character of the ocular movements (Krieger, et al., 1958). Only Robinson and Fuchs have clearly documented the saccadic nature of electrically elicited eye movements. A similarly detailed analysis of the ocular response to stimulation of the posterior cortical areas from which eye movements have been elicited is required to define the relation of these regions to the generation of saccades.

2. Ablation Studies

a. Frontal Excisions:

Ten years after his initial report on electrical stimulation of the brain, Ferrier, working with Yeo (1884), unilaterally ablated the FEF in the monkey. This caused a temporary deviation of the head and eyes of the animal toward the side of the lesion. These effects usually lasted no more than nine days. After bilateral FEF ablation, the eyes and head were unable to move from side to side and were fixed in midposition with relation to the body. In orienting to lateralized stimuli, the animal moved his body, head, and eyes as a whole. This phenomenon was also temporary, with apparently normal function returning in a few days.

Bianchi (1895) reported the results of unilateral frontal lobe ablations which included the FEF in dogs and monkeys. He, like Ferrier and Yeo, noticed rotary movements of the animals toward the side of the lesion. Bianchi attributed this to visual and "psychic" disturbances;

the animals appeared to have a contralateral homonymous hemianopsia.

It must be noted that these early ablations were rather crude, and the excised areas were most likely not limited to the FEF alone.

Kennard and Ectors (1938) more thoroughly investigated the results of lesioning the FEF in rhesus monkeys. They confirmed the observations that unilateral ablation of this area was followed by turning of the head and eyes and ambulatory circling movements toward the side of the lesion. They used the term "forced circling" to describe the apparently purposeless movements displayed by these animals. These symptoms were severe for two to three days after surgery. Within two to three weeks, the eye and head deviations slowly diminished and disappeared. The circling behavior lasted for several months.

With simultaneous bilateral ablation of the FEF, Kennard and Ectors described the animal as sitting motionless with a fixed gaze. This central fixation (also found by Ferrier and Yeo) was similar to the results of bilaterally electrically stimulating homologous points of the FEF. In addition to the fixed gaze, the animals rarely blinked. The eyes would follow an object, however, but always returned to the fixed central stare. In other words, the animal, if confronted with an object, could apparently follow it reflexively, but could not shift gaze voluntarily to fixate an extrafoveal object. A similar visual defect occurred

after unilateral ablation of the FEF. The monkeys displayed a transient visuomotor defect that Kennard and Ectors believed was not a hemianopsia, but was instead an inability to respond to visual stimuli which was an indirect result of the oculomotor disturbance. This defect also occurred with lesions in the frontal lobe beyond the FEF and was most severe following frontal lobe extirpation. Crosby (1953) called this deficit a "pseudohemianopia" and attributed it to interference with the fibers connecting the PEF with the FEF. Although the visual fields, blink reflexes, following movements, and fixation of the eyes were all seemingly intact, Crosby interpreted these findings by suggesting that the animals had no way of translating the visual impulses into voluntary responses because either the association pathways or the FEF, both of which are essential to these voluntary responses were destroyed.

In a recent careful analysis of deficits associated with FEF lesions, Latta and Cowey (1971a) provided evidence for a possible perceptual contribution to this unilateral visual spatial neglect. On perimetric testing of monkeys with FEF lesions, a contralateral hemiambyopia was discovered. This was not due to the abolition of eye movements toward the contralateral side, since the monkeys were able to shift their gaze to that direction. Also, the neglect could not have been due to ipsilateral deviation of the eyes, since fixation was controlled. Thus, the FEF appear to be involved in visual perception as well as oculomotor

control. It is interesting to note that Jenker and Katschera (1965) reported a case of frontal lobe lesion in man which resulted in a hemianopic field defect that persisted for the five years prior to publication of the report. Frontal lobe lesions in man, however, are not ordinarily thought to result in such visual defects. Teuber, Battersby, and Bender (1960) noted that patients with frontal lobe lesions displayed longer searching times in the contralateral visual field.

Latto and Cowey (1971b) further demonstrated that unilateral FEF lesions produced a shift in fixation up to 10° to the ipsilateral side. Bilateral FEF lesions caused the monkeys to look below the point of fixation. There was a tendency for the eyes to remain in their primary, straight ahead position (as had also been found by Kennard and Ectors and by Ferrier and Yeo). The authors suggested that these defects might have been due to an imbalance in the oculomotor system in which the FEF might exert a tonic influence on ocular fixation.

Of interest is that in both studies by Latto and Cowey, the experimentally defined field defect and fixation changes persisted long after observable oculomotor deficits displayed by the monkey in his home cage had disappeared.

b. Parieto-Occipital Ablations:

Although there are numerous reports of visual field deficits caused by posterior cortical lesions in experimental animals, few studies have specifically been

concerned with oculomotor dysfunction following ablation of these regions. In an experimental study of optokinetic nystagmus, Henderson and Crosby (1952) bilaterally ablated the parts of occipital (area 18) and preoccipital (area 19) regions which they had found to be related to ocular deviation. These lesions abolished optokinetic responses toward either side. Unilateral lesions of the same areas caused a loss of optokinetic response away from the side of the lesion.

Smith and Cogan (1959) concluded from their study of 31 clinical cases, in which the site of the lesion was verified by neurosurgery or autopsy, that a defective optokinetic response is indicative of parietal lobe lesions. All but five of the patients with verified occipital, frontal or temporal lesions did not show abnormal optokinetic reactions. Those five cases had rather extensive lesions which most likely impinged upon the parietal lobe. Only one patient with a parietal lobe lesion showed a normal optokinetic response.

In contrast to other workers, Pasik and Pasik (1964) reported a failure to find any alterations, even transient, in oculomotor function as tested by observations of spontaneous eye movements and optokinetic and vestibular nystagmus following ablations of the frontal, parietal and temporal lobes of monkeys which included the classic eye fields. A unilateral ablation of the occipital cortex produced a transient gaze preference toward the side of the lesion. Bilateral excision of the entire striate cortex abolished the optokinetic response, which returned in three out of

nine monkeys after several months. From these data, the Pasiks concluded that "there are no specific centers for eye movements in the cerebral cortex." They added that "oculomotor function is widely distributed over the entire cortex," an assertion based upon the effects produced by one-stage destruction of one cerebral hemisphere, which caused gross impairment of oculomotor function, including deviation of the eyes to the side of the lesion and disruption of the optokinetic response. These results are hard to reconcile with previous and subsequent work employing localized cortical excisions. The Pasiks explained this discrepancy by suggesting that other workers did not limit ablations to cortical areas, but might have inadvertently lesioned subcortical structures as well. This seems doubtful in all cases. Certainly, the results of electrical stimulation (particularly Robinson and Fuchs' study of the FEF) would indicate that there is some specialization of the cortical representation of oculomotor function.

c. Conclusions from Ablation Experiments:

Lesions of the FEF in the monkey largely support the data obtained from electrical stimulation in implicating this area in the oculomotor control system. A striking feature of these experiments, however, is the lack of permanent deficits, which suggests some redundancy of the mechanisms subserving eye movements.

The results of Latta and Cowey also necessitate a reassessment of the functional role of the FEF. Previously,

it had been thought that this region was concerned principally with oculomotor functions, whereas these new experiments indicate that the FEF also plays a role in visual perception.

Oculomotor deficits due to lesions of the posterior regions, particularly the preoccipital and parietal regions, seem to be most often manifested by abnormal optokinetic responses, implying that posterior regions mediate reflexively determined eye movements which are dependent upon visual stimulation. Indeed, FEF lesions often result in exaggerated following eye movements, which the animal seems unable to stop voluntarily once his attention is directed to the moving visual target. Heightened optokinetic responses also were noted following bilateral FEF excision (Henderson and Crosby, 1952). This suggests that the FEF has an inhibitory influence over the posterior regions. Thus, the issue of redundancy of functional systems is not a simple one. In the intact animal, the frontal and posterior eye fields may be functionally distinct systems, each called into play under different circumstances. Unfortunately, firm conclusions obtained from ablation experiments are not possible. Although oculomotor deficits do occur following lesions of specific cortical areas, we do not know how the remaining portions of the system compensate for the excision of one portion of the oculomotor control system. For this reason, studies in the intact, behaving animal are necessary to elucidate the physiologic mechanism of interaction between the cortical oculomotor areas, and to elucidate their relation

to the subcortical regions implicated in the control of eye movements.

3. Recording of Brain Potentials

a. EEG and Average Brain Potential Studies:

The technique of recording electrical activity associated with specific observable events (i.e., stimuli or movements) is perhaps the most fruitful means for seeking an understanding of the brain mechanisms underlying behavior, since concurrent variations in brain activity can be defined in relation to specific sensorimotor sequences. Conventional EEG recording and, more recently, the use of averaging techniques have led to the identification of potentials associated with eye movements in man. In 1949, Evans noted sharp occipital waves following eye movements across a patterned field. These "lambda" waves appeared most prominently during scanning well-illuminated contrast fields (Evans, 1952, 1953; Roth and Green, 1953; Scott, Groethysen and Bickford, 1967) and thus appeared related to visual input. The amplitude and the latency of the averaged lambda response changed with variations in stimulus parameters (Gaarder, Krauskopf, Graf, Kropfl, and Armington, 1964; Scott, Groethysen, and Bickford, 1967) in much the same way as the visual evoked response to light. This leads one to infer that the lambda response is a visual evoked response (VER) due to changes in retinal stimulation associated with shift of gaze. Furthermore, the topography of the lambda

response was found by Remond and Lesevre (1970) to closely resemble the cranial distribution of the VER.

Potential changes preceding the onset of voluntary eye movements were briefly mentioned (without description) by Scott and Bickford (1967) and Vaughan (1969). Barlow and Ciganek (1969), using a bipolar pair of electrodes placed at mid-occipital (Oz) and mid-parietal (Pz) positions, recorded a slow negative wave which began 150-200 msec prior to the initiation of voluntary eye movements, performed either in the presence of visual input or in the dark. This potential was absent for compensatory eye movements which occurred upon passive turning of the head. Since the bipolar Oz-Pz linkage was the only placement used, it is not possible to determine either the location of maximum activity or whether this potential reflected a greater negativity at the occipital region or a greater positivity overlying the parietal region. In addition, components common to both recording sites would not be seen. The results obtained from preliminary experiments as part of the present study were reported by Kurtzberg and Vaughan (1970).

b. Recording from Single Neurons:

Neural unit activity in the visual cortex associated with eye movements has been studied in monkeys by Wurtz (1968, 1969 a,b). He found 32% of the cells he probed increased their discharge rate (excitatory response) and 20% of the cells decreased their discharge

rate (suppression response) following eye movements across a patterned field. Forty-eight percent of the cells showed no change in rate. Neurons did not respond when an eye movement was made across a white, homogeneous field. Thus, the stimulus conditions required to elicit a response were similar to that needed to elicit the EEG lambda response. Wurtz compared the activity of these cells during the presentation of a stationary stimulus and found, under that condition, all the cells have an excitatory response. If the stimulus was moved rapidly in front of a stationary eye, all three types of neurons responded exactly as they did during an eye movement across the stimulus field. This appears to be further support for considering the lambda response as a VER to pattern shift across the retina.

Bizzi (1967, 1968) studied unit activity in the FEF of unanesthetized monkeys. Out of a total of 2,500 neurons examined, only 102 (approximately 4%) were found to be related to eye movement. He described two characteristic forms of cellular response. Type I cells fired during saccadic eye movements in a given direction and also during the fast phase of nystagmus. Type II cells were steadily active when the eyes were oriented in a given direction and systematically changed their firing rate during smooth pursuit movements and the slow phase of nystagmus. Bizzi reported that only two cells fired prior to eye movement. His conclusion, based on these observations, that the FEF plays no role in the initiation of eye movements, seems to

conflict with the results obtained from stimulation and ablation experiments. Perhaps an alternative interpretation of Bizzi's results can be derived from Robinson and Fuchs' study. Since they found that localized electrical stimulation of sites within the FEF yielded saccadic eye movements of a specific direction and amplitude, the number of cells related to the initiation of a given eye movement might be quite small in number. Inasmuch as Bizzi did not systematically study eye movements of varied size and direction, it would be a matter of chance to record from an FEF cell implicated in initiating the observed movement.

Research Plan

Through the study of electrocortical potentials associated with voluntary eye movements in man, it might be possible to clarify the role of the cerebral cortex in the initiation and control of saccadic eye movements. The technique of averaging EEG synchronized with specific stimuli or motor acts is well suited to this task, since it can provide a high degree of temporal resolution between the onset of the eye movement and the associated brain potentials. Furthermore, the cranial distribution of these potentials can be mapped in order to estimate their sources (Vaughan, 1973).

Knowledge of the relative timing of the cerebral electrical activity associated with eye movements is essential for

assessing the role of the cortex in eye movement control. If antecedent potentials associated with eye movements are found, as has been demonstrated for extremity movement (Kornhuber and Deecke, 1965; Vaughan, Costa, Gilden, and Schimmel, 1965; Gilden, Vaughan, and Costa, 1966; Vaughan, Costa, and Ritter, 1968), this would imply that cortical mechanisms are indeed involved in the control of ocular movements. These gross potential data, when viewed in conjunction with the unit recordings of neurons which discharge prior to eye movements in subcortical structures (Schiller and Koerner, 1971; Wurtz and Goldberg, 1971) will provide a more complete picture of the saccadic eye movement initiation and control system.

This study will evaluate the possible role of the cerebral cortex in the initiation of saccadic eye movements and in the processing of saccade linked visual input in man, employing a topographic analysis of saccade-related scalp recorded potentials. The aims of this investigation will be

(1) To define the location of the intracranial sources of potentials preceding eye movement and of the lambda response. The latter will be compared with the response evoked by a passive pattern shift so as to substantiate the suggestion that the lambda response is an evoked response due to the change in retinal stimulation caused by movements of the eyes across a patterned field.

(2) To analyze the timing of the antecedent potentials relative to the saccades to test their possible reflection

of neural processes which initiate saccadic eye movements.

Based upon the topographic and temporal characteristics of the scalp recorded potentials, the visuomotor mechanisms they may depict will be discussed.

CHAPTER II

METHOD

1. Subjects

Five normal adults (4 male and 1 female) were subjects (Ss) for these experiments. Detailed results are presented for three Ss and two Ss participated in confirmatory studies. All were experienced in similar studies of event related potentials. Since the eye movement task was demanding, considerable practice was required to achieve the required precision of ocular excursion without associated blinks or other adventitious movements.

2. Experimental Conditions

All of the studies were performed in a sound damped electrostatically shielded recording chamber (Industrial Acoustics) from which all light was excluded. Ss were seated in front of a binocular tachistoscope (built to specification by Scientific Prototype). Since a preliminary study showed that ocular movements remained fully conjugate (i.e., of equal amplitude and velocity) when a monocular as compared to a binocular fixation field was employed, all of the experiments were performed using a monocular fixation and stimulus fields (to obviate the necessity of aligning separate fields for each eye). The right eye was positioned by means of a dental

impression bite board affixed to a three dimensional manipulator (Brinkman) so as to place the plane of the pupil in the focal point of the beam emanating from the eyepiece (Maxwellian view). Three main experimental conditions were employed as follows:

a. Eye Movement Across a Vertical Grating:

Subjects performed horizontal eye movements across a patterned field designed to elicit a prominent lambda response (Evans, 1952; Scott, et al., 1967). The stimulus field consisted of a $11^\circ \times 11^\circ$ black and white vertical grating with each stripe subtending a visual angle of $30'$. Two horizontally oriented fixation points were superimposed on the grating with a separation of 3° . Mean field luminance measured at the position of the pupil by an International Light Research Photometer was 5 mL. In order to evaluate the effect of luminance on the lambda response (cf., Gaarder, et al., 1964), movements were also performed across the stimulus field with a 2 log reduction in luminance achieved through the use of a Kodak Wratten neutral density filter.

Ss were instructed to shift fixation from one fixation point to the other, maintaining fixation at each point for a minimum of two seconds. This permitted a one second EEG record to be obtained before and after each eye movement. An experimental run consisted of a series of 50 movements in each direction between the fixation points. Four to eight runs were obtained for each recording condition,

which provided a total sample of 200 to 400 eye movements.

b. Eye Movements in Total Darkness:

In order to assess the contribution of visual input to the potentials recorded in association with eye movements, an attempt was made to obtain data with eye movements comparable to those of condition (a) performed in total darkness. These movements could be considered purely voluntary, in the absence of visual cues for reflexive guidance of fixation. One S (JK) was successfully trained, using verbal feedback while monitoring the size of each movement, to perform saccades of the required amplitude 3° in total darkness.

c. Visual Evoked Response to Pattern Reversal

These experiments were performed to permit a comparison of the VER to a shift of the grating pattern with the lambda response elicited by the active movement of the eyes across the grating. Two stimulus fields of the tachistoscope were employed, each comprising a 11° x 11° grating with 30' vertical black and white stripes. One of these was the same field employed in the eye movement condition (a), while the other was arranged so as to be complementary to the first (i.e. the black stripes of one overlying the white stripes of the other). Ss fixated midway between the two fixation points and the fields were alternated every 2.5 seconds which approximated the interval between eye movements in condition (a). Each recording run comprised 200 pattern shifts. As in condition (a) field luminance was 5 mL for the high luminance condition and

reduced by 2 log units for the low luminance recording.

Supplementary studies were performed to analyze in more detail the distribution of the potentials which appeared in the periorbital region. A control study of neck muscle activity was also performed.

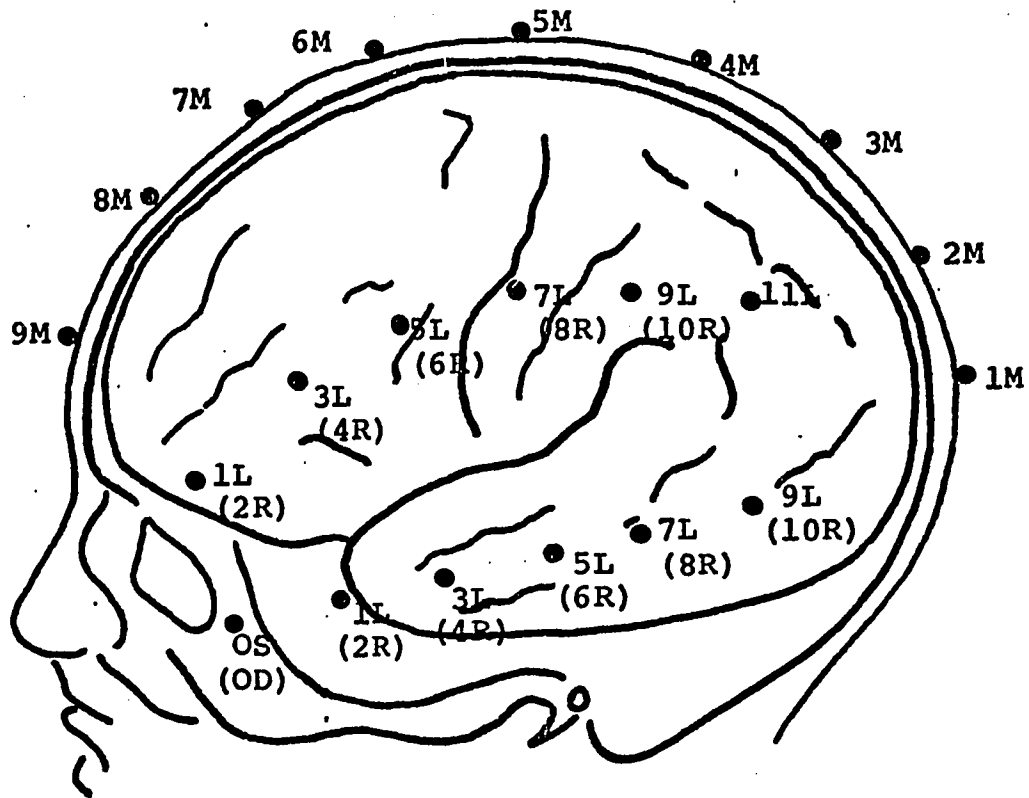
a. Electrooculogram Distribution:

The cranial distribution of the electro-oculogram was determined in order to distinguish between cortical potentials and potentials generated by the eye due to rotation of the corneoretinal dipole (the electro-oculogram or EOG). In this task, Ss performed horizontal eye movements of 20°, 10° and 3°. The larger eye movements provided a clearer picture of the EOG distribution on the scalp since the ocular potentials were substantially larger than the concurrent EEG. The electrode montage consisted of 33 bilateral placements as depicted in Figure 1. S sat in front of a white screen with black fixation points placed either 20°, 10° or 3° apart. All other methodological procedures were the same as those used in the experimental conditions. Potentials associated with 50 eye movements of each size were averaged and amplitude measurements of the EOG distribution were made. Isopotential maps of these distributions were constructed as described in Section 4 of the Methods.

b. Distribution of Periorbital Potentials:

Sharp potentials associated with eye movements were observed in electrode placements near the

Figure 1: Electrode array consisting of 33 bilateral placements used in the electrooculogram distribution studies. Electrodes were placed in three linear arrays: (1) sagittal, (2) lateral on a line between the outer canthus and the mid-occiput, and (3) intermediate, midway between (1) and (2). Electrodes were placed 4.5 cm, 3 cm, and 4 cm apart for the sagittal, lateral, and intermediate chains respectively. Linked ears were used as reference.



orbit. The timing and distribution of these potentials were studied using additional electrode placements in order to define the nature of these potentials. The 15 electrode placements are depicted in Figure 2. These were referenced to either the linked ears or the chin. Experimental and recording procedures were as in condition (a). Trials of 50 or 100 eye movements were averaged and amplitude measurements of the periorbital potential distribution around the eyes were obtained.

c. Neck Muscle Activity During Eye Movements:

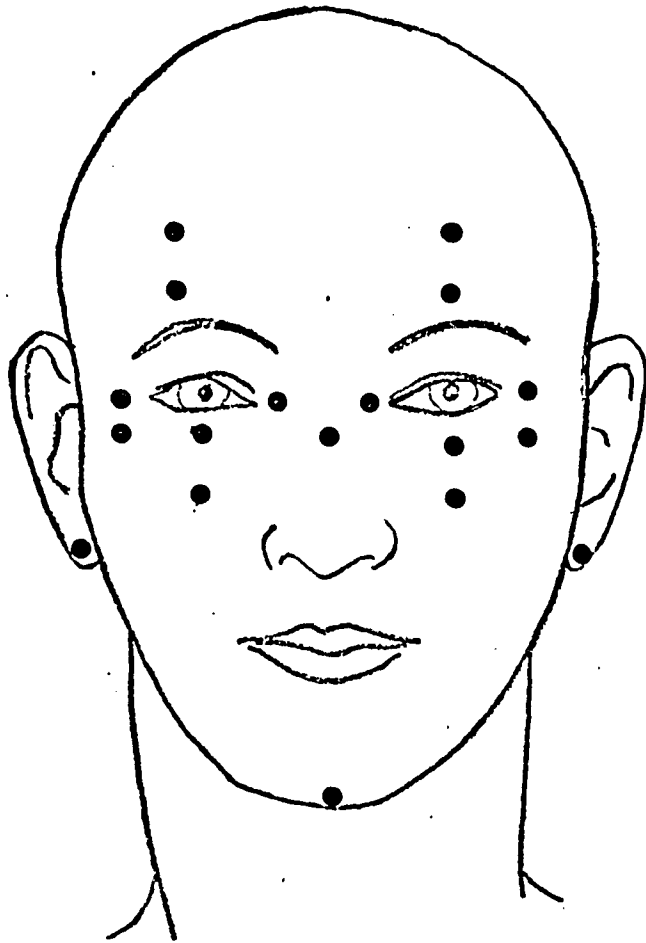
Since head and eye movements are often coordinated in regarding the visual world, it was necessary to evaluate the possibility that concurrent head and neck movements occurred as the eyes were moved. Electromyographic recordings from right and left sternocleidomastoideus and right and left splenium capitus muscles were taken during an experimental session. Electrodes (Beckman) were applied over these muscles and EMG records were monitored on-line during the experimental runs. Since bursts of EMG indicating muscle activity are clearly seen on unaveraged traces, it was not necessary to average these data.

3. Recording Methods

a. Electrode Application and Placement:

The scalp EEG recordings were obtained using felt-padded silver-silver chloride disk electrodes (Henderson/

Figure 2: Electrode placements for studies of the distribution of periorbital potentials. Electrodes were referred to linked ears or to chin.



Montreal Neurological Institute). These were fixed in place with an elastic band custom fitted to the head of the S following vigorous cleansing of the skin with acetone and local mild abrasion with saline electrode jelly. The headband permitted the placement of electrodes in any desired array by slipping the electrodes through holes in the band so as to lie beneath it in close contact with the scalp. The felt electrode pad was soaked in saline prior to application and additional electrode jelly applied so as to obtain good electrical contact. The measured resistance of all electrodes was maintained below 5K ohms.

In order to obtain an adequate topographic map of the cerebral potentials under investigation, an array of 23 electrodes was used, deployed over the left hemi-cranium as depicted in Figure 3. Additional placements were employed in some studies to compare the potentials recorded from homologous sites overlying the two hemispheres. Linked ear electrodes were employed as reference.

The electrooculogram (EOG) was recorded from Beckman Miniature Biopotential electrodes (silver-silver chloride) placed at the outer canthus of each eye, as close to the eye as possible. In the recordings of brain potentials, the EOG was recorded using "bipolar" technique, whereas for mapping of the EOG potentials, the linked ears were employed as reference as for the brain potential recordings.

b. Recording Apparatus and Procedure:

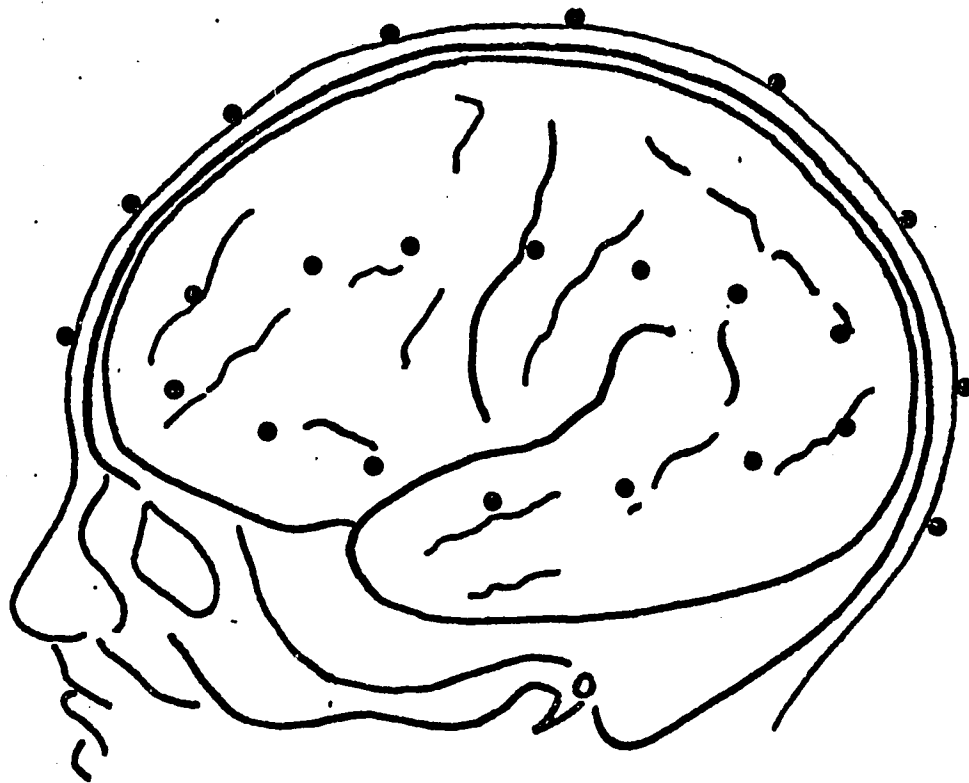
The configuration of the recording and data

Figure 3: Electrode montage used for experimental conditions, comprising three chains of 23 scalp and 2 orbital electrodes.

Sagittal chain: 9 electrodes placed equidistantly from inion to supraorbital ridge.

Intermediate chain: 9 electrodes from mid-occipital placement (Oz) to supraorbital ridge, halfway between the sagittal and lateral chains.

Lateral chain: 9 electrodes from Oz to supraorbital ridge, two-thirds distance between the sagittal chain and tragus.



processing equipment is depicted in Figure 4. The EEG and EOG signals were amplified by seven low level preamplifiers (Tektronix Type 2A61) set for a bandpass of .06-600 Hz. The amplifier time constant (approximately 4 sec) under these settings is adequate to record the slow potential shifts often observed in relation to movement and other behavioral tasks. System gain was 20K for the EEG and 8K for the EOG.

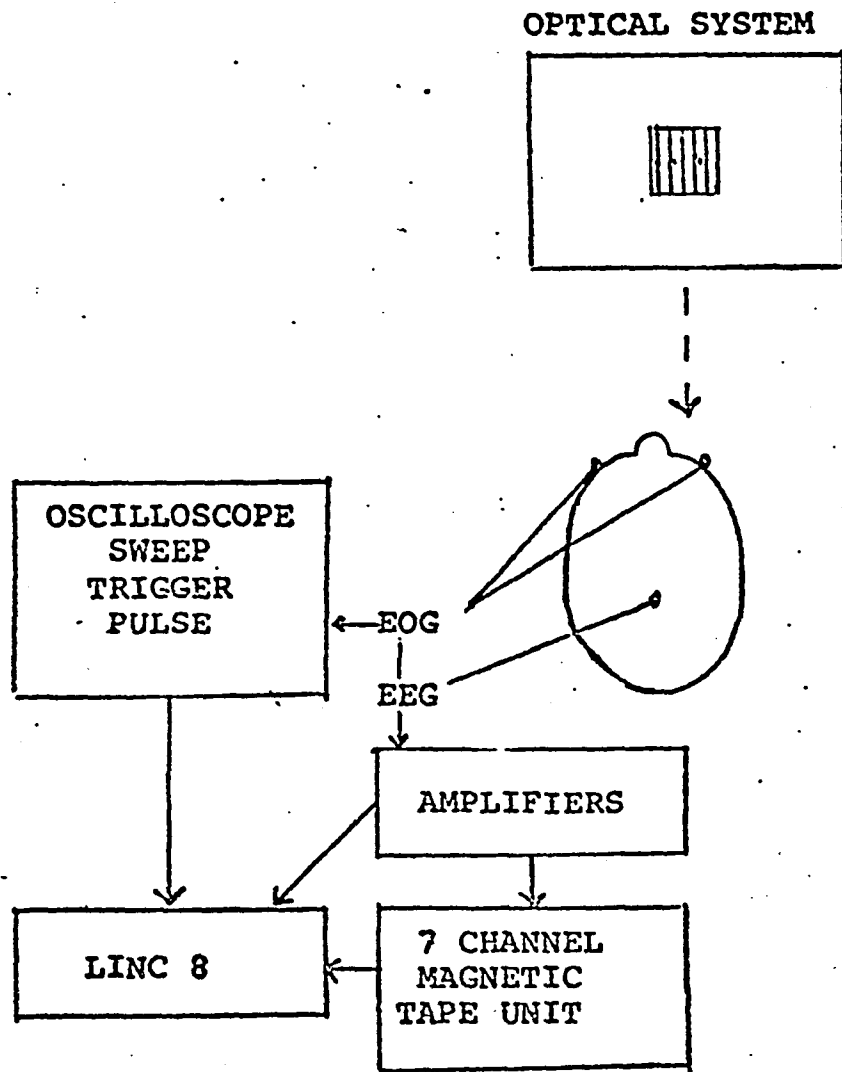
At the beginning of each run, the electrophysiologic data were visually checked to insure freedom from line and muscle artifacts. During the run, the EOG and three channels of the EEG were continuously monitored on a 4-trace oscilloscope (Tektronix 3A74 plug-in).

The EOG was employed to trigger the time base (Tektronix 2B67) of a second oscilloscope to provide a trigger pulse at the initiation of each eye movement in a given direction. The trigger sensitivity was set as close to the baseline of the EOG as possible without producing spurious triggering by fluctuations in the baseline. This technique produced highly consistent triggering which was continuously monitored during each run.

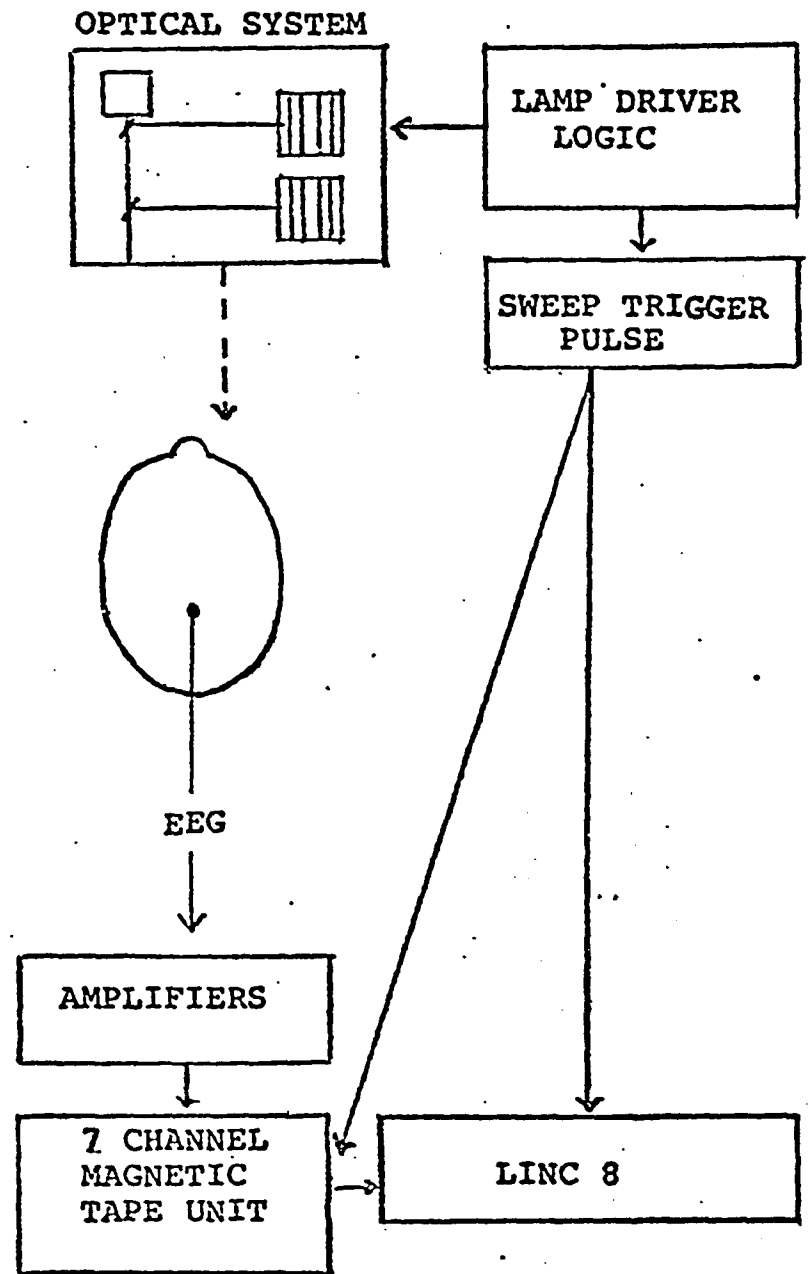
All of the amplified signals were recorded at 3 3/4 ips on magnetic tape employing a 7-track FM tape unit (Honeywell Model 7600) with a frequency response of DC-2.5 KHz.

During each experimental run, the EOG and EEG data were concurrently averaged on-line using a LINC-8 digital computer. The computer was programmed to con-

**Figure 4: Block diagram of recording and data processing equipment. Left: Eye movement experiments
Right: Pattern shift experiments**



EYE MOVEMENT EXPERIMENTS



PATTERN SHIFT EXPERIMENT

tinuously sample the analog data, to convert it to digital measures of voltage at a predetermined sampling rate and to store a selected number of samples in memory. The stored data were continually updated so as to discard the earliest sample, while adding the latest sample. When the trigger pulse indicating the occurrence of an eye movement was sensed by the computer, it held the set of data previously in memory and continued to sample and add to memory the data which followed the trigger for a specified time. Thus, a single epoch of data comprised a pre-trigger and post-trigger period. Each epoch was then added to the sum of data from previous trials and finally divided by the total number of trials to provide the average EOG and EEG for a run.

Since only seven data channels could be concurrently recorded, it was necessary to utilize six sets of recordings to obtain data from the entire montage of 23 electrodes. The six sets of recordings were taken in three sessions on three separate days. Each session consisted of recordings taken from nine electrodes (placed either along the mid-sagittal, intermediate or lateral lines). The session was divided into two sets of recordings with the EOG, Oz lead, and a trigger pulse indicating the onset of the eye movement appearing in both. In order to standardize the data across runs, a common electrode (Oz) was employed for all recordings so that the data from other electrodes could be scaled across runs to the mean value recorded at Oz. The remaining channels

were utilized for four EEG placements. Thus, two sets were required during each session to obtain recordings from all nine electrodes. Each set consisted of four to eight runs of 50 eye movements in one direction (a total of 100 eye movements in the two directions per run). Runs were averaged to obtain any value of N up to 400 for each direction of eye movement and 800 for both directions.

Additional studies were run during the session (e.g., pattern shift) as indicated in Section 2.

4. Data Analysis

The reliability of the average eye movement potentials is affected both by variability representing residual background EEG activity and variability of the eye movement potentials themselves. The relative contribution of these two sources of variance can be estimated by examination of either the standard deviation or the \pm reference (Schimmel, 1967) computed for each time sample across the epoch. Any systematic increase in variability during the period of the eye movement potentials can be presumed to represent variance contributed by the variability of these potentials, whereas the variance before and after them represents the variability contributed solely by the background EEG. Similar inferences can be drawn from the \pm reference which provides an independent estimate of the variability. The \pm reference eliminates the mean component through alternate

addition and subtraction of the data in successive epochs, and provides an unrectified representation of the random residual activity with the same statistical properties as the average itself (Schimmel, 1967 and unpublished).

In Figure 5, the average \pm reference and standard deviation are depicted for 25, 100 and 400 epochs to illustrate the statistical features of the data. Subject WR was selected for illustration since his background EEG was the largest (reaching a peak to peak amplitude of 50 μ V during periods of strong alpha activity) of the three Ss. Inspection of the averages for increasing N clearly discloses the progressive diminution in amplitude of the background rhythms which precede and follow the eye movement related potentials. This reduction is proportional to the square root of the number of epochs as predicted by the usual applications of signal theory to random time varying functions. The \pm reference depicts a comparable reduction in residual background, as well as indicating no increase in variability during the eye movement potentials. Similarly, the standard deviation reveals no increment in variance during the time-locked potentials, indicating an essentially negligible variability in the eye movement potentials themselves as compared with the background EEG. The standard deviation, however, provides an excessive estimate of the variability of measurements of the phasic components of the average response because it contains a substantial contribution from very low frequency activity (baseline

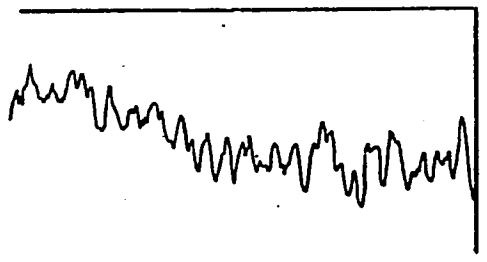
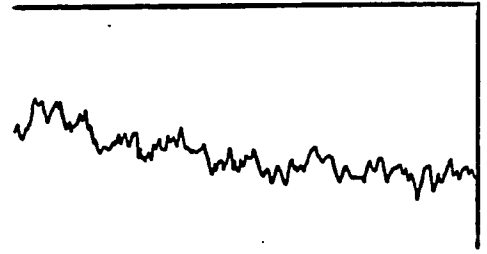
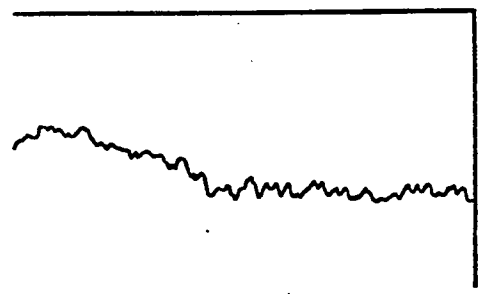
Figure 5: Mean, \pm reference, and standard deviation of eye movement potentials for averages of 25, 100 and 400 trials. Eye movements were performed under condition (a). Note that the means show a progressive diminution of background activity proportional to \sqrt{N} occurring before and after the potentials associated with eye movements. The \pm reference also shows a reduction in residual background with increasing sample size and in addition, shows no increase in variability during the eye movement related potentials. The standard deviation shows no increase in variability during the eye movement related activity.

50V
200
MSEC

N=400

N=100

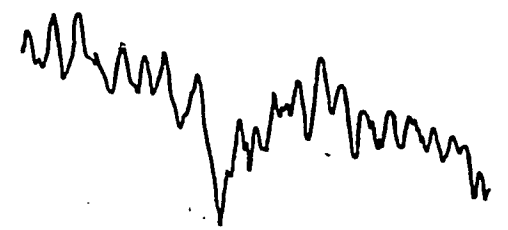
N=25



S.D.



REF
±



MEAN

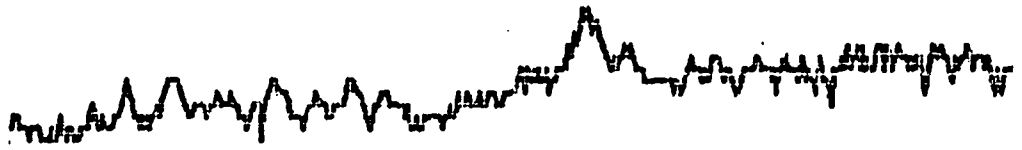
sways) due to the very low bandpass (.06 Hz) of the amplification system. A better estimate of the errors to be expected within the frequency range of the phasic eye movement potential components (approximately 2-20 Hz) can be obtained from the \pm reference and the range of rhythmic fluctuations in the standard deviation which reflect the higher frequency components of the variance. Thus, we can see that for an N of 25, the maximum peak to peak amplitude of residual background activity is approximately 5 uV, for 100 epochs, 2.5 uV, and for 400 epochs, 1.25 uV. These figures represent the maximum measurement errors which could occur when the amplitude measurements were made at points at which, by chance, a maximum excursion of the residual background was present. An accurate statistical description of the probability distribution of amplitudes of the \pm is given by the Rayleigh distribution (Schimmel, unpublished), but for the purpose of the present study, no effort has been made to further evaluate the probability distribution of errors, since the maximum possible error itself is sufficiently small as to insure that the amplitude measurements made on averages comprising 200 or 400 epochs were indeed quite reliable. A further demonstration of variability of averages can be derived from the standard deviation statistic, which as previously noted, exaggerates the measurement errors. Since the standard error of the mean can be estimated as the standard deviation divided by the square root of the

number of samples entering into the mean, this statistic is approximately 2 uV for 25 epochs, 1 uV for 100 epochs, and 0.5 uV for 400 epochs. Since the distribution of means is essentially normal according to the Central Limit Theorem, we can conclude that 95% of observed mean values will fall within ± 2 standard errors. An empirical check on this inference was made by actually computing the point by point standard deviations of eight averages of 50 epochs for each subject. The computed standard deviations of the means (i.e., the standard error), are depicted in Figure 6. These values are somewhat larger than the estimates derived above, which reflects some degree of non-stationarity in the data. As described in the next section, however, any variability in the averages across runs was eliminated when used for mapping the amplitude distributions by scaling the averages across runs.

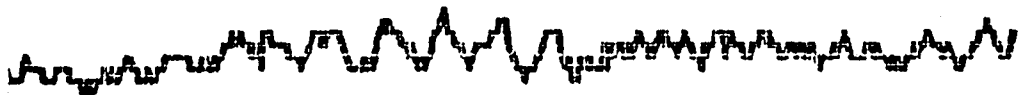
Analysis of Sources of Eye Movement Potentials

A volume conduction model representing the brain and its coverings as a sphere surrounded by three shells (CSF, skull, and scalp) has been developed and applied to topographic studies of human brain potentials by Vaughan and colleagues (1969; 1970; 1973). The model assumes that the cortical sources can be adequately represented by current dipole layers with two main configurations. One case represents surface cortex and consists of a circular cap of varying angular subtense and distance from the center

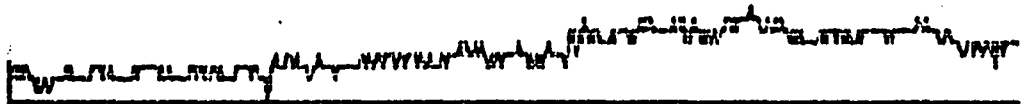
Figure 6: Standard errors of the mean eye movement related potentials computed from eight averages of 50 epochs for subjects WR, RS, and JK.



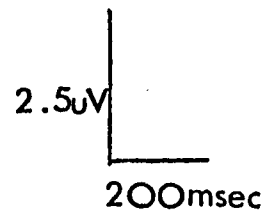
WR



RS



JK



of a sphere. The second case represents sulcal cortex and comprises a plane layer oriented normal to the sphere. A representation of any cortical source can be obtained by a sum of these two cases. In order to estimate the sources of a particular brain potential, its empirical distribution is compared with a theoretical field configuration.

In the present study, the sources of brain potentials associated with saccadic eye movements were estimated. The procedure involved the identification of components within the averaged eye movement related potentials, based upon the criteria of a constant latency across recording sites and a monotonic decrement in amplitude from a maximum point.

The following components were identified:

1. Antecedent potentials
 - a. slow potential shifts
 - b. initial positive wave
 - c. sharp positive wave
2. Lambda response

These components were measured peak to peak as indicated in Figure 7. In those cases in which the brain potentials were contaminated by EOG, the data obtained from eye movements in both directions were averaged so as to cancel the EOG while preserving the brain potentials, which were found to be the same for movements in either direction (see Results - Inter-hemispheric Comparisons).

The amplitude measurements for each montage were then scaled against the common electrode (Oz) to correct for

Figure 7: Eye movement potentials associated with 3° eye movements across a vertical grating. Recording from electrode placed at theinion illustrates the amplitude measurements of the following components:

AP - Antecedent potentials

(a) slow potential shift

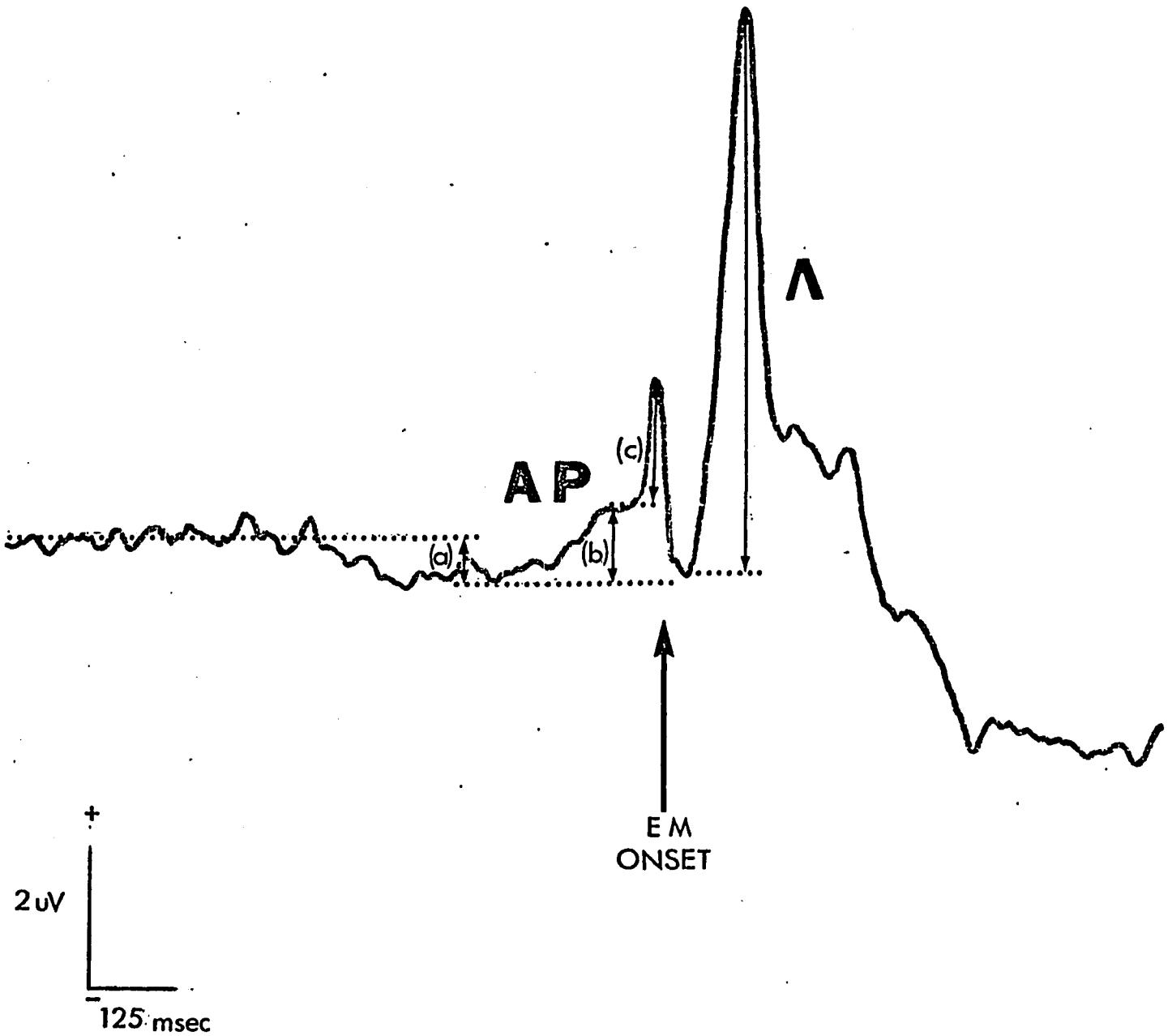
(b) initial positive wave

(c) sharp positive wave

Λ - Lambda response

Subject: WR

Average of 400 trials



variations in amplitude across runs. These scaled measurements were converted into percentages of the amplitude at its maximum point, and isopotential maps constructed for each component. The empirical data, in the form of a series of amplitude measurements along several axes of the contour map were then compared with a family of theoretical distributions. Based upon the results of stimulation data of the cortical eye fields, the cap model approximating surface cortex was deemed appropriate. The comparison of the empirical data against the theoretical distribution yielded estimations of cortical sources for eye movement potentials. (See Results - Estimation of INtracranial Sources for application of this procedure).

CHAPTER III

RESULTS

Potentials Associated with Eye Movement Across a Patterned Field

Potentials associated with voluntary saccadic eye movements across a patterned field (condition [a]) both preceded and followed the saccades. We designated the activity occurring prior to the initiation of eye movements as antecedent potentials, and the activity which followed saccades as the lambda response, in conformity with the terminology introduced by Evans (1952). The morphology, time course, and distribution of these potentials are described in the following sections.

Antecedent Potentials

Potentials occurring prior to the initiation of eye movement typically consisted of a slow potential shift followed by two phasic deflections -- a slow positive wave and a brief sharp positive wave (Figure 8).

Slow Potential Shifts

The earliest change in the averaged brain potentials associated with eye movement was a slow potential shift (SPS). Although shifts almost always appeared in some form, their time course, polarity, and amplitude varied within each subject and among the three subjects. Most often,

Figure 8: Eye movement potentials associated with 3° movements across the grating, recorded from electrodes overlying mid-frontal (F), mid-parietal (P), and mid-occipital (O) regions. Note the inconstant slow potential shift preceding eye movement. The phasic antecedent potentials begin approximately 200 msec prior to saccade initiation and consist of a slow positive wave and a brief sharp positive wave. The lambda response follows the eye movement in the occipital leads. It is also evident in the parietal trace for Ss JA and RS.

Reference: Linked ears

Eye movement onset at line

Calibration: JK, JA, JSz, RS: 2.5 uV
WR: 5 uV

Time Scale: 200 msec

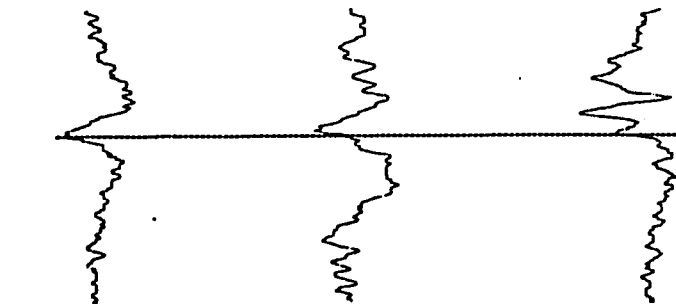
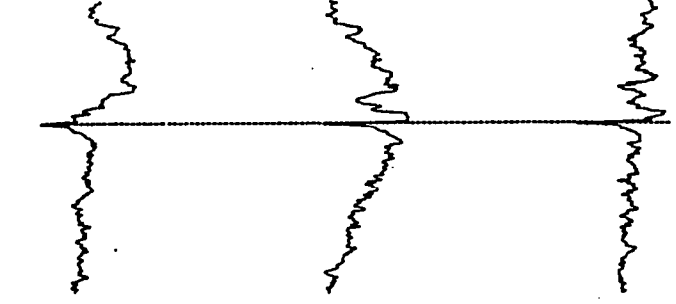
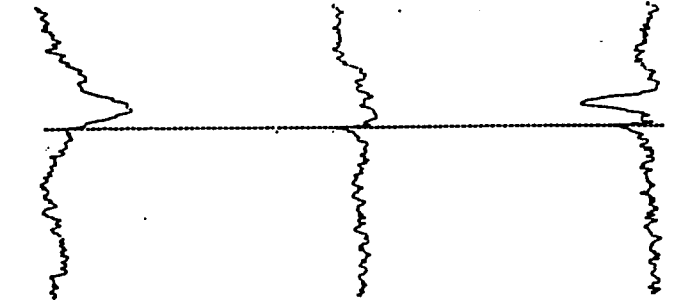
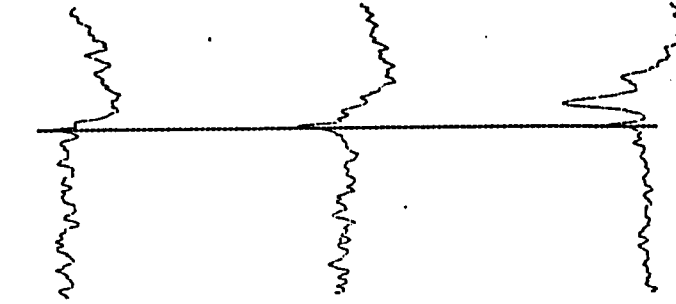
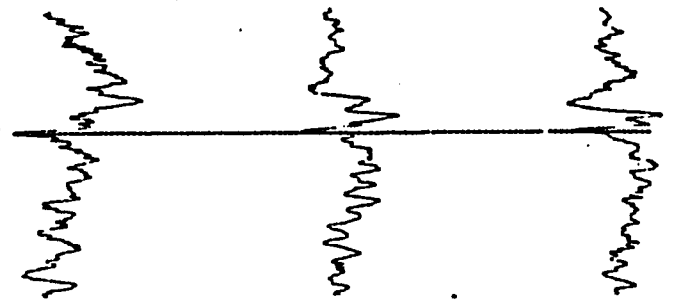
RS

WR

JSz

JA

JK



F

P

O

L

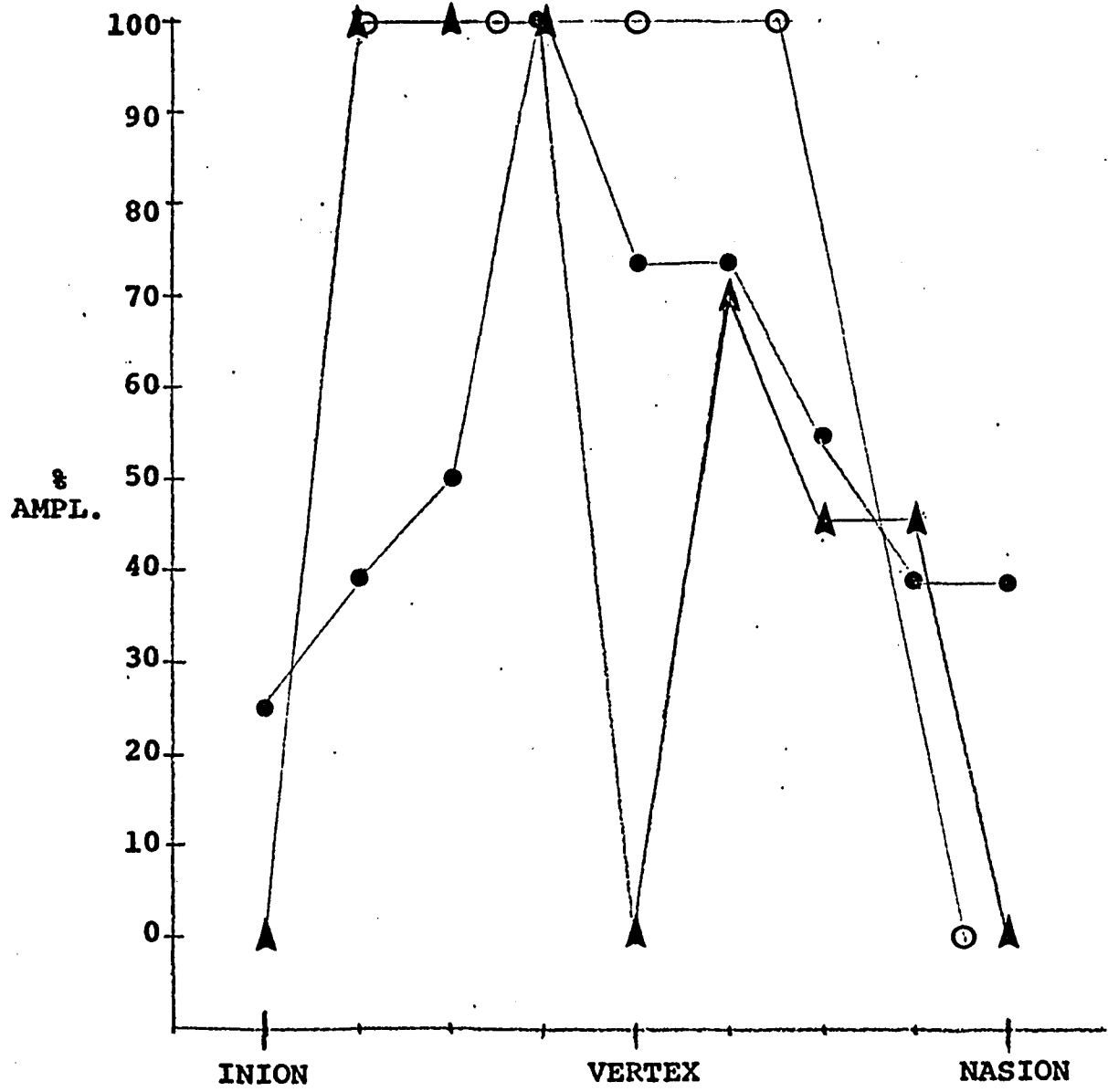
however, the SPS were negative and began 600-1000 msec before the saccade, and ended with the appearance of the first positive component of the phasic antecedent potentials. Occasionally, although beginning as a negative shift, a reversal in polarity occurred at 300-500 msec before the saccade. This activity had a ramp-like appearance, slowly becoming more positive until it culminated in the first positive wave of the phasic antecedent activity. Often, however, the shifts would have over-riding rhythmic activity (i.e., alpha rhythm in the posterior leads) which blocked at the onset of the first positive deflection.

A distinction between the slow positive shift and the first positive wave could also be made when the antecedent activity began as a positive shift. In this case, the positive shift began no earlier than 600 msec prior to the saccade. It also had a ramp-like appearance and culminated as the first component of the phasic antecedent potentials as described above.

In all cases, whether the shifts were negative or positive, they were small in amplitude, ranging between .35 and 5 uV.

The SPS were too variable to permit reliable mapping of their scalp distribution for all montages. The mid-sagittal electrode array, however, showed consistent temporal and polarity characteristics of the SPS for all Ss so that amplitude measurements of these data could be made. Figure 9 depicts the distribution of these shifts for the three Ss. A widespread posterior-central distribution is evident,

Figure 9: Distribution of negative slow potential shifts along the mid-sagittal line depicted individually for Ss RS, JK, and WR. Measurements are expressed as percentages of the maximal slow potential shift amplitude for each S.



○ JK
 ▲ RS
 ● WR

which in two Ss (RS and WR) was saddle-shaped, with maxima overlying the parietal and posterior frontal regions.

Phasic Antecedent Potentials

The phasic antecedent potentials consisted of two components: a positive wave followed by a brief sharp positive deflection. In two Ss (RS and WR), these two segments could be distinctly identified. In one S (JK), the two components were not clearly differentiated.

The onset of the initial positive component varied between 60 and 190 msec before saccades. For each electrode montage and for each S, this component began earliest in the parieto-occipital region. This was seen most strikingly in the intermediate and midline chains.

The brief sharp positive component preceded the beginning of saccades by 10-30 msec in the two Ss who showed distinct segments. This wave also began earliest in the parieto-occipital region. The peak of this sharp wave was seen at the precise moment of eye movement initiation in one S (RS); 10 msec after the onset of saccade in WR; and 20 msec after the beginning of eye movement in JK. This temporal relationship was consistent for each S for all electrode placements in which this component was seen.

Interhemispheric Comparisons

In order to detect any differences in the electrical activity between the hemispheres related to eye movement, bipolar recordings were taken between homologous points

from both the parietal and frontal regions which displayed the maximal antecedent activity. Electrodes were placed 10 cm anterior to Oz and 6.5 cm from the midline in the parietal region, and 20 cm anterior to Oz and 5 cm from the midline in the frontal region. These placements were supplemented by monopolar recordings from each electrode of the two pairs, with the linked ears serving as reference.

The bipolar recordings between homologous areas revealed no antecedent activity in either the parieto-occipital or frontal regions (Figure 10). The only activity apparent in the bipolar recordings was conducted electrooculographic potentials, particularly in the frontal area. Due to the dipolar nature of the corneo-retinal potential, the conducted EOG activity over each hemisphere was opposite in polarity with horizontal eye movements, and summed in the interhemispherical recordings. Monopolar traces from each electrode displayed the pattern of eye movement potentials previously described.

In addition, data from experimental condition (a) were also analyzed with respect to direction of eye movement. EEG was averaged separately for eye movements from right to left and from left to right, and no differences were found in the antecedent potentials associated with eye movements in either direction.

Thus, both hemispheres appear to be equally active during voluntary saccadic eye movements in either direction.

Figure 10: Bipolar recordings from homologous points over left and right hemispheres depicting potentials associated with 3° eye movements across the grating.

Top trace: Recording between left (PL) and right (PR) parietal region.

Bottom trace: Recording between left (FL) and right (FR) frontal region.

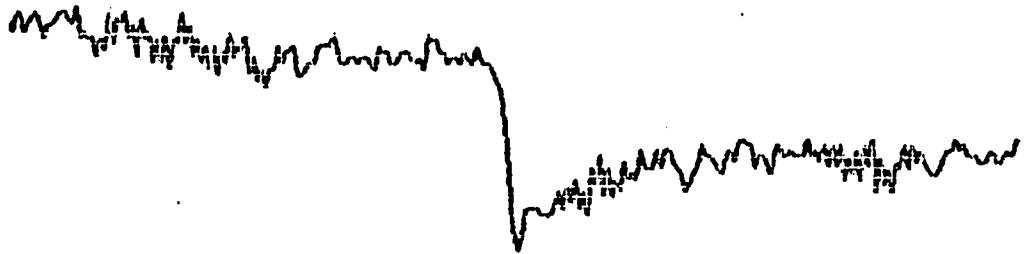
Subject: JK

Each trace comprises 200 trials

Note absence of activity antecedent to the onset of eye movement. Conducted electrooculographic potentials are seen in the traces, larger in amplitude in the frontal region.



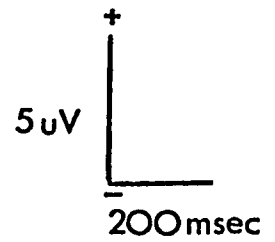
PL-PR



FL-FR



EM ONSET



Potentials Associated with Eye Movement in the Absence of Visual Input

One subject (JK) was able to perform consistent saccadic eye movements of approximately 3° in the absence of visual input. The antecedent potentials associated with these movements were similar in morphology and temporal characteristics to the brain activity recorded with eye movements over the grating (Figure 11). There was, however, no lambda response after the eye movement. Instead, a slow negative wave, which lasted for approximately 300-400 msec, followed the antecedent potentials. Superimposed upon this negativity was periodic activity at a frequency of 10 Hz, which was the same as the prominent alpha rhythm displayed by JK on the raw EEG. As in the raw EEG, this activity was most prominent in the occipito-parietal region. On the averaged traces, the activity decayed in amplitude as a function of time following the eye movement, which probably reflects a progressive decrease in the time locking of these waves to the saccade. The latency of the first clear wave of this rhythmic after-potential was approximately 180 msec. Since the peak latency of the initial positive component of the lambda response evoked by eye movements across the grating at the lower field luminance was approximately 200 msec, its shorter latency would seem to preclude the possibility that this activity represents a residual lambda response.

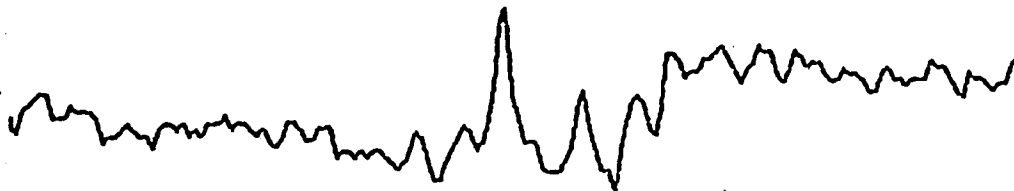
As in the case of movements over a patterned field, the potentials preceding the initiation of saccades in

Figure 11. Eye movement potentials associated with approximately 3° movements performed in the dark, recorded from mid-occipital, posterior parietal, and posterior frontal regions. Note negative wave with over-riding alpha activity.

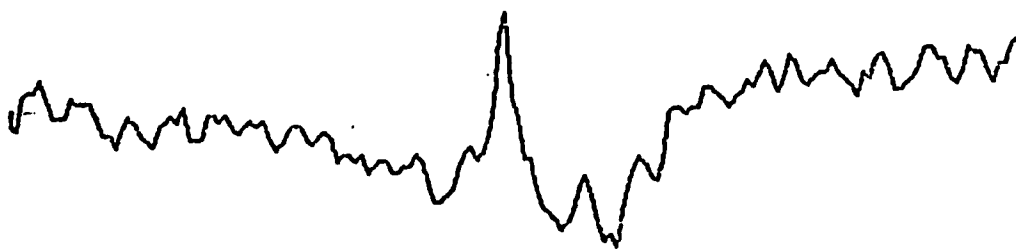
Subject: JK

Averages of 400 trials.

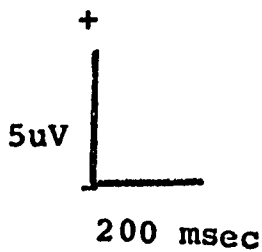
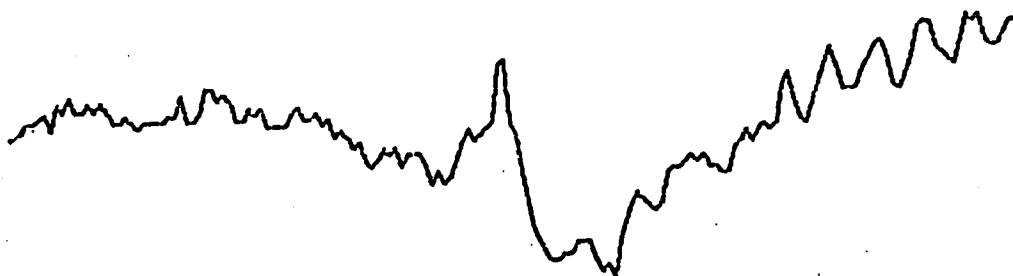
OCCIPITAL



PARIETAL



FRONTAL



↑
EM ONSET

the dark began with a slow shift, usually negative in polarity and largest in the posterior leads. The time course was the same as those shifts seen when S performed saccades with the grating as a field. The phasic antecedent potentials also possessed similar morphological and temporal characteristics as those previously described for condition (a). The initial positive component began 80-170 msec before initiation of movement. The sharp positive deflection was seen at 20-50 msec prior to saccades, and had its earliest onset at 45-50 msec prior to saccades over the posterior regions of the scalp. It is of interest that subject JK showed distinct slow and sharp components of the phasic antecedent potentials in the dark, whereas these components were not distinguishable with eye movements across the grating.

Distribution of Antecedent Potentials

The cranial distribution of the antecedent potentials associated with eye movements over the grating is depicted for each montage for the three Ss in Figure 12. These plots represent measurements taken for the total amplitude of the antecedent potentials after it was determined that the initial positive and the brief sharp components had similar distributions (Figure 13).

The cranial distribution of the potentials recorded in the dark was essentially the same as those recorded under conditions of illumination.

Figure 12: Cranial distribution of phasic antecedent potentials for Ss RS, JK, and WR. Measurements from midline, intermediate, and lateral electrode arrays are depicted. Amplitude expressed as percentage of maximum calculated separately for each S.

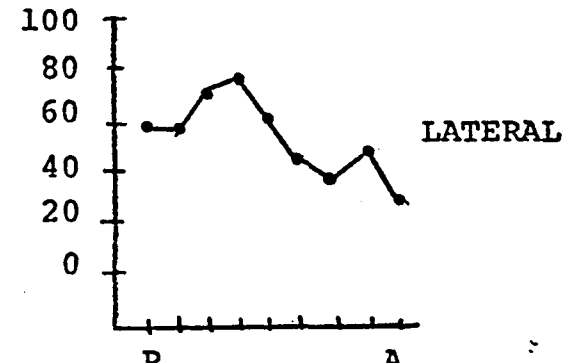
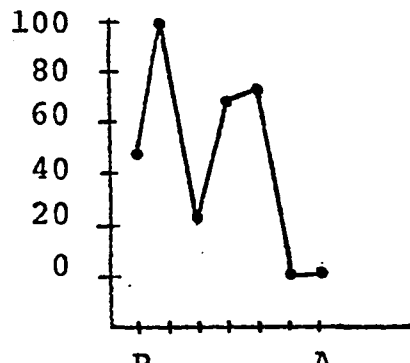
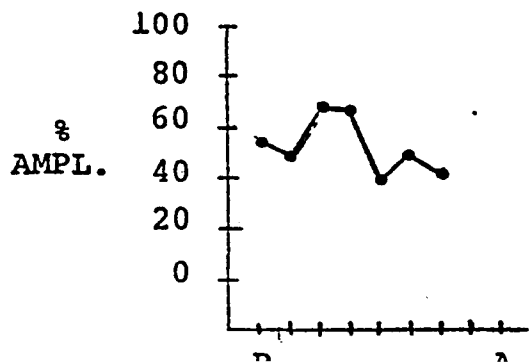
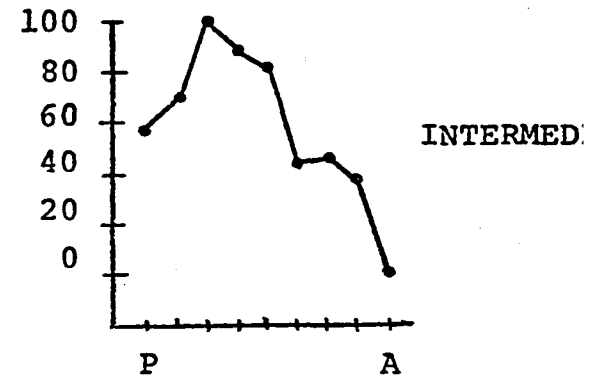
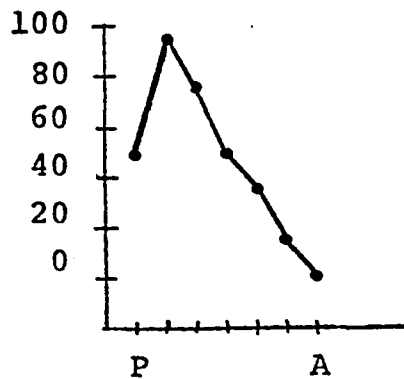
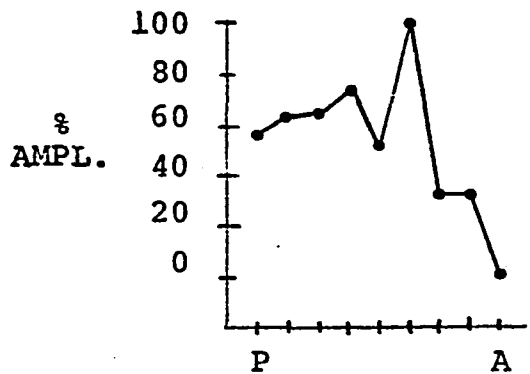
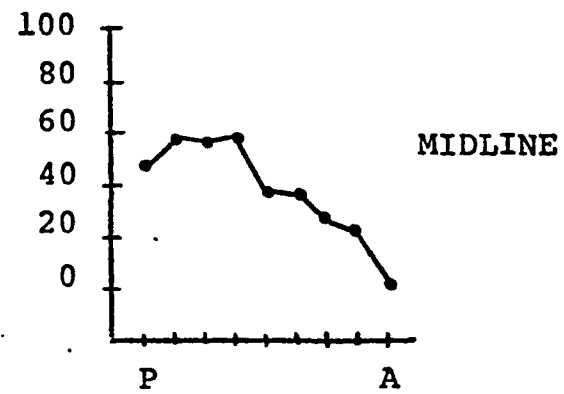
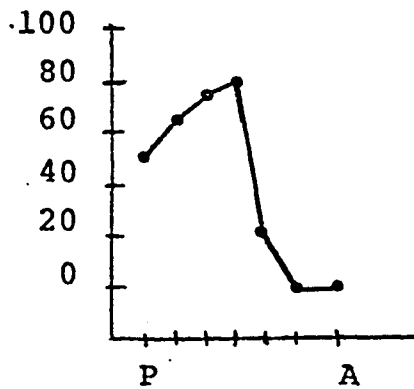
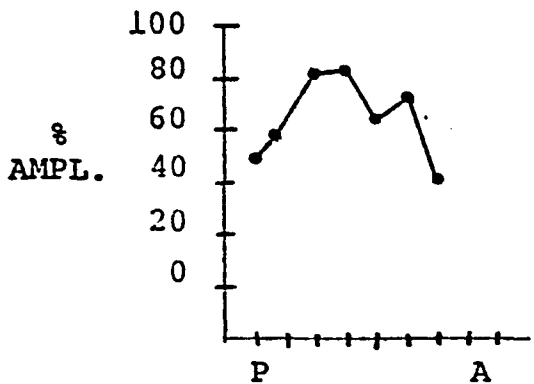
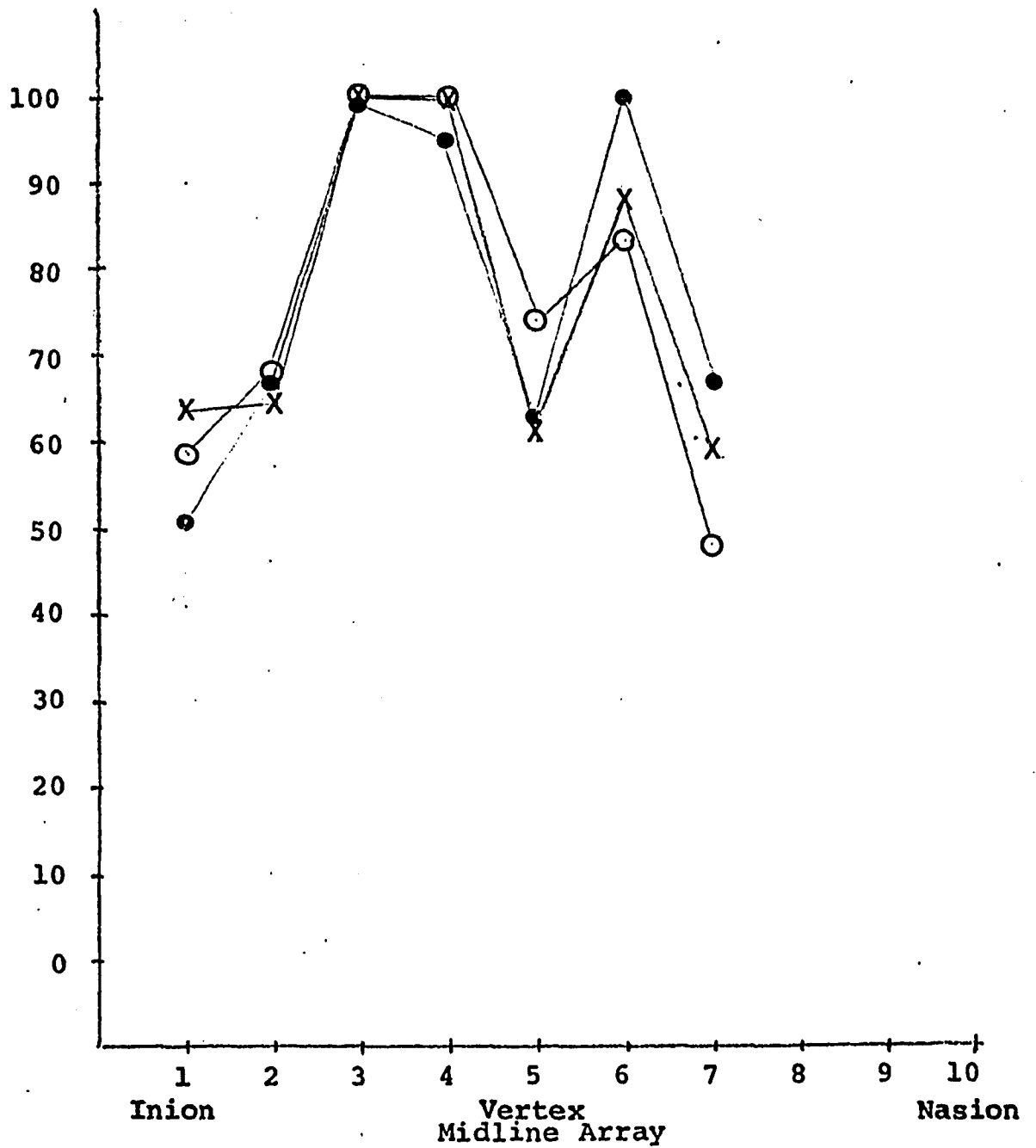


Figure 13: Cranial distribution of antecedent potential components measured separately along the mid-sagittal line.

Subject: RS

AMPL.



- Initial Positive
- X Brief sharp positive
- Total

Isopotential maps of the antecedent potentials associated with eye movements over the grating for each S are depicted in Figure 14. The parieto-occipital region was identified as the area of maximum amplitude for the antecedent potentials. A second focus was evident in the frontal region. Activity in this region tended to be smaller and more circumscribed than the posterior focus.

Estimation of Intracranial Sources

Employing the isopotential maps, which depict the scaled amplitude measurements for specific components of the eye movement related potentials, planes were passed through the maximum points of each distribution, both in the coronal and antero-posterior directions, to permit measurements of the potential gradients along these lines. Figure 15 depicts an isopotential map of the antecedent potentials for subject JK and the lines along which the gradients are to be plotted. Taking the posterior source as an example, amplitude plots for the antecedent potentials along the two axes are depicted (Figure 16).

In the coronal plane, the gradients were bilaterally symmetrical, since both hemispheres were found to be equally active during eye movements. There will be an overlap of potentials due to each hemispherical generator at and near the midline. The amplitude contributed by each source is 50% of the total amplitude measured at the intersection of the two fields at the midline. The empirical gradients are represented according to the angular equivalent of the

Figure 14: Isopotential maps for the antecedent potentials recorded in condition (a).

Subjects: RS, WR, JK

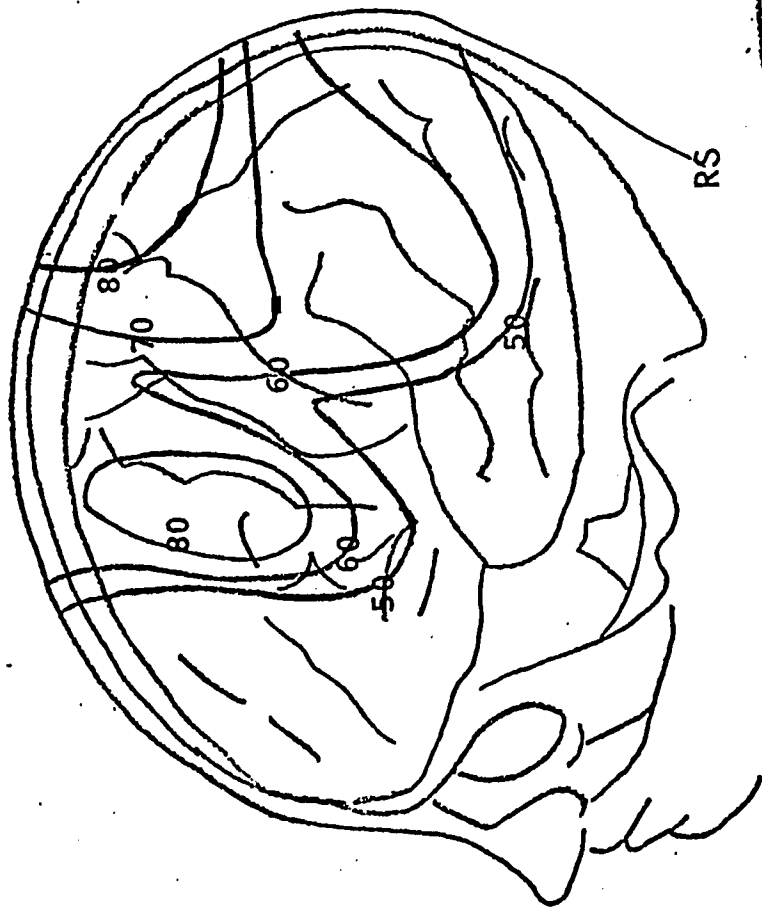
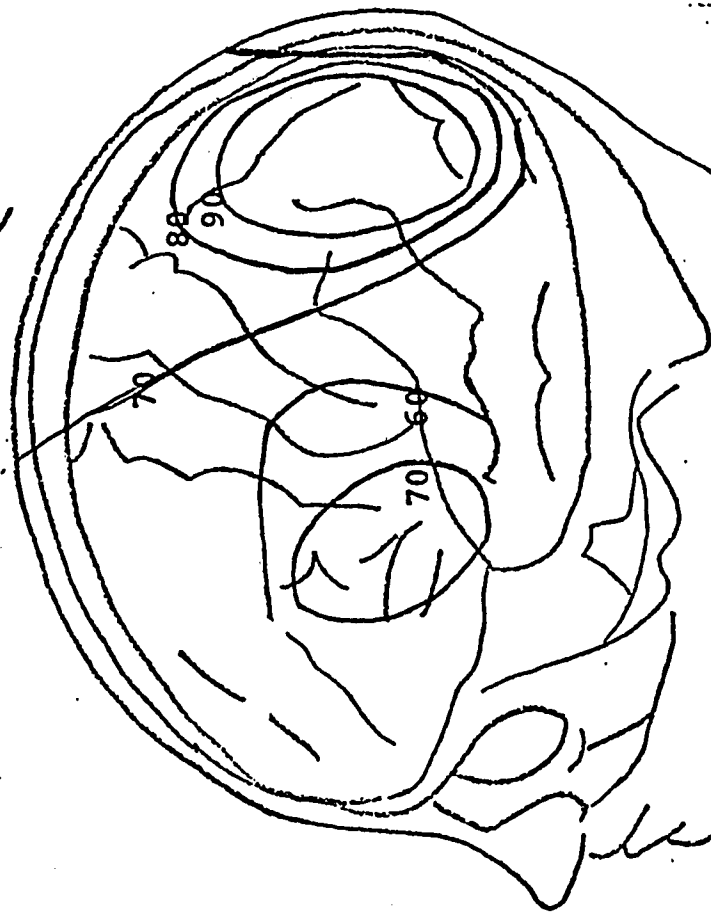
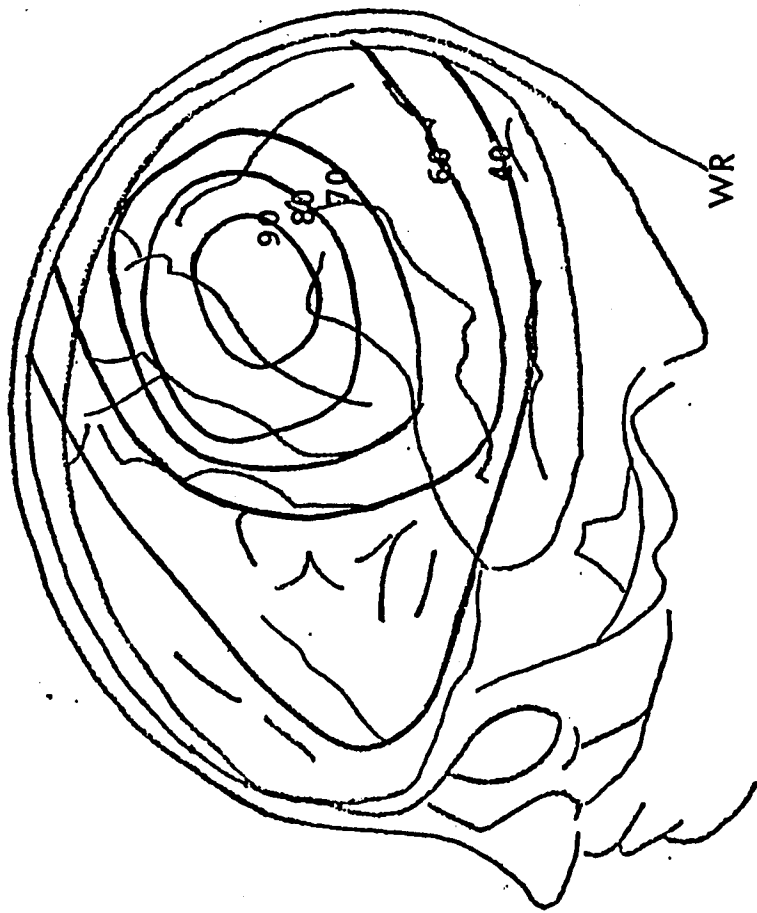


Figure 15: Isopotential map of the antecedent potentials for subject JK illustrating the analysis of intracranial sources. Lines have been passed through the maximum points of the posterior focus in the coronal (A-A') and antero-posterior (B-B') directions to facilitate the plotting of amplitude gradients along the major axes of the posterior field.

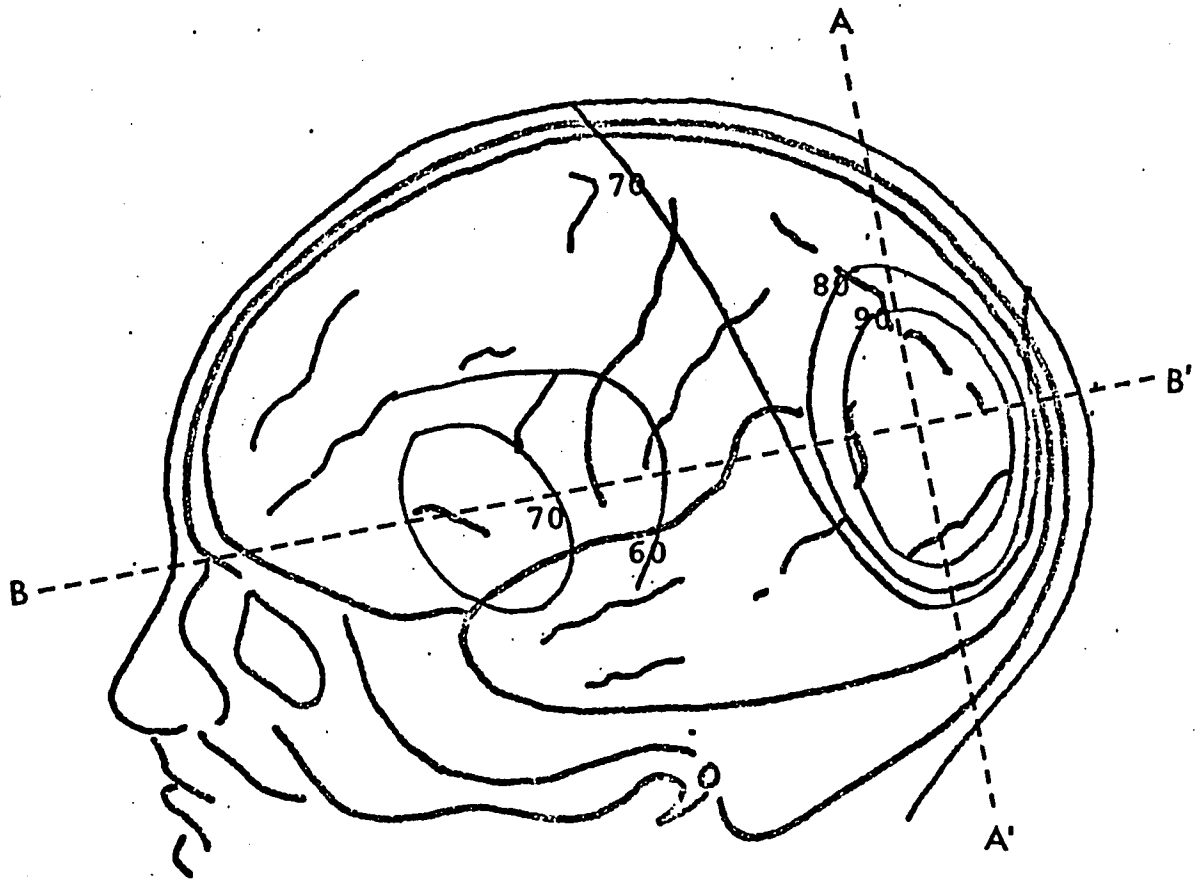
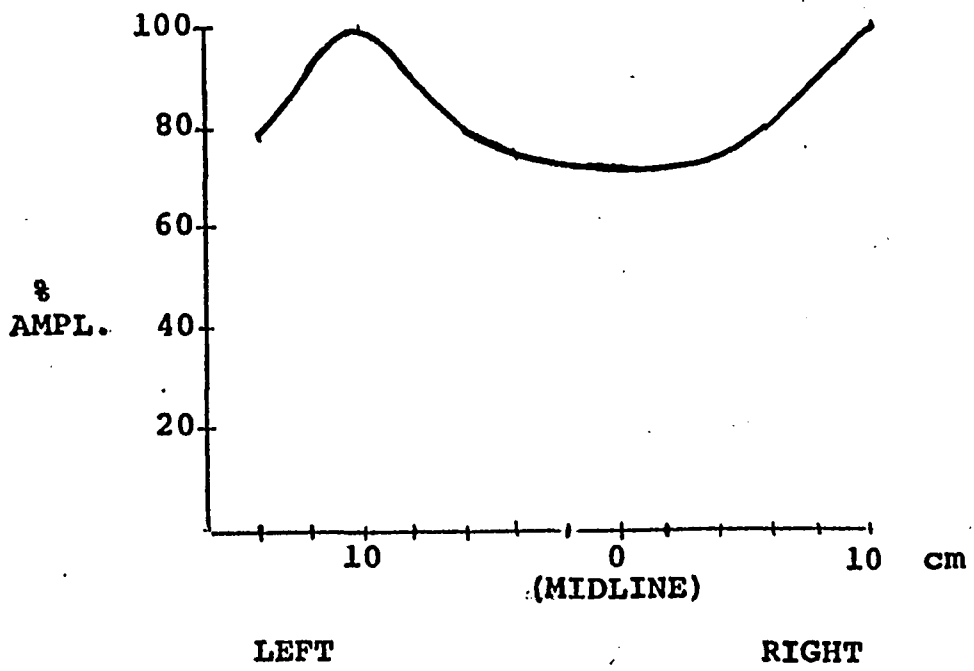


Figure 16: Empirical potential distributions of the antecedent potentials along coronal (A) and antero-posterior (B) axes for subject JK. See Figure 15.

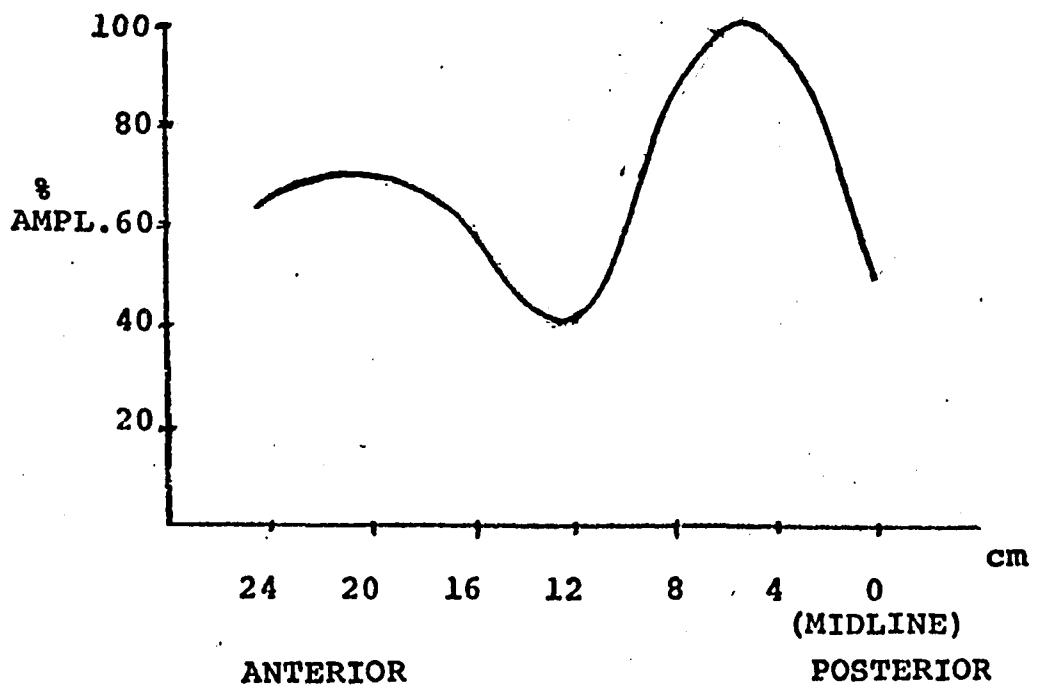
A: The abscissa represents distances along line A-A' with origin at the mid-sagittal line of the head.

Smooth curves were drawn to best represent the empirical data.

B: Amplitudes plotted along B-B' line, the origin taken at the midline in the occipital region. Smooth curves were drawn to represent the empirical data.



A



B

distances on the scalp along the principal dimensions of the plots (Figure 17). The solid lines represent the inferred fields generated within each hemisphere. The maximum point of each field and the point at the midline define the empirical distribution which can be compared with the family of theoretical curves computed from the volume conduction model. These curves represent potential distributions generated by sources of varying angular subtense (Figure 18). For the coronal direction, the curve corresponding to a source size of 96° best fits the data. The selected theoretical curves are then appropriately positioned with respect to each other and added to confirm a satisfactory match with the empirical distribution.

In the antero-posterior direction, two distinct areas of maximal amplitude were observed, one in the posterior frontal region and the second in the parieto-occipital region. The presence of two distinct cortical generators can thus be inferred. The amplitude due to each generator at the points of intersection along this line are presumed to be unequal, since the empirical data showed that maximum amplitude of the frontal field to be approximately two thirds that of the posterior field. Thus, the inferred curves are drawn to reflect the proportional contribution of each generator (Figure 17). When these data are compared to a family of theoretical curves, it is found that a source size of 24° best matches the data.

Thus, the total extent of the posterior source for the

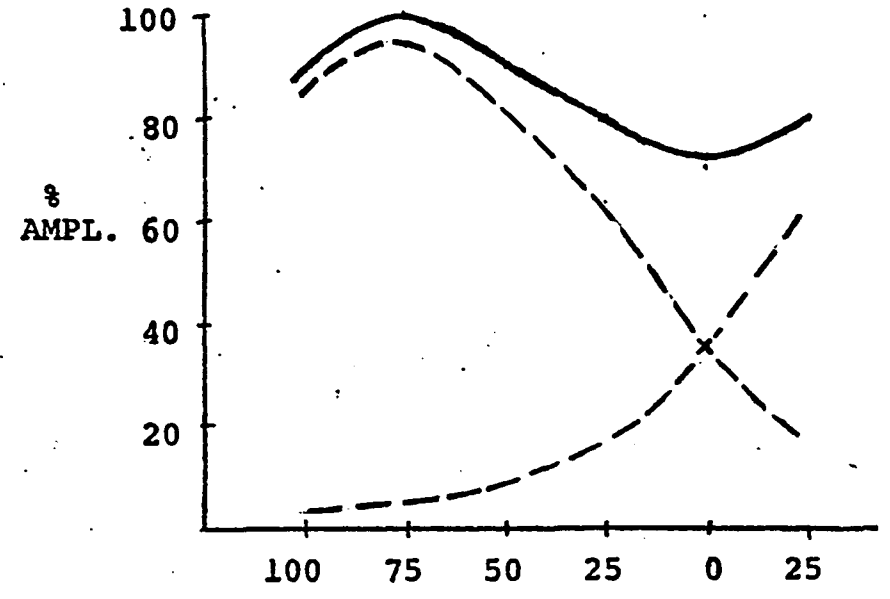
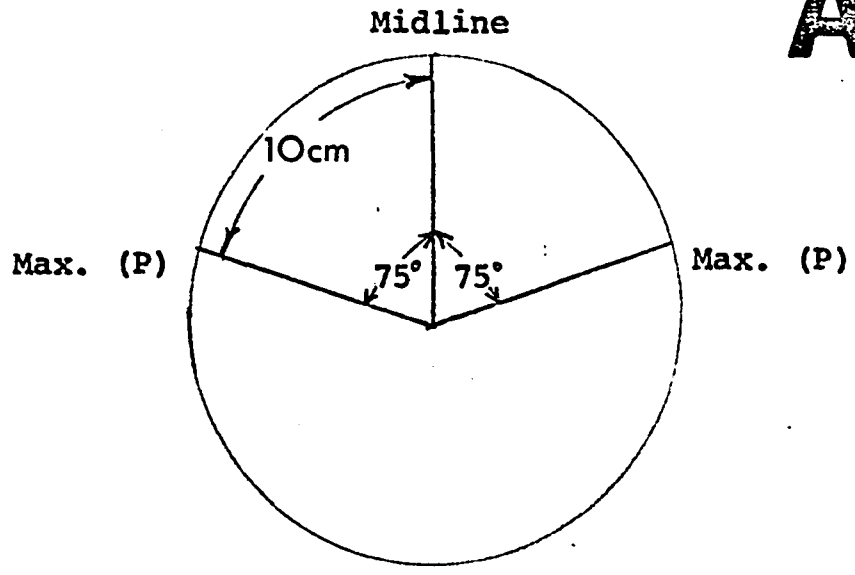
Figure 17: Left: Diagrammatic representation of the loci of maximum potential for coronal (A) and antero-posterior (B) planes. Distances as measured on the scalp in centimeters are depicted, as well as the distance from the midline expressed as an angular equivalent. The coronal plane passes through the midline in the parietal region and the antero-posterior plane through the occipital region. Max (P) and Max (F) refer to the loci of maximum amplitude in the parietal and frontal regions respectively. In the coronal plane, Max (P) occurs 10 cm from the midline or an angular equivalent of 75° . In the antero-posterior plane, Max (P) is 6 cm or 33° from the midline and Max (F) is 14 cm or 120° from the midline.

Right: Empirical gradients of the antecedent potentials (as depicted in Figure 16) plotted as the angular equivalent of distance along the scalp. Solid lines represent the observed data. Broken lines represent theoretical distributions which sum to match the empirical data.

A: Coronal

B: Antero-posterior

A



B

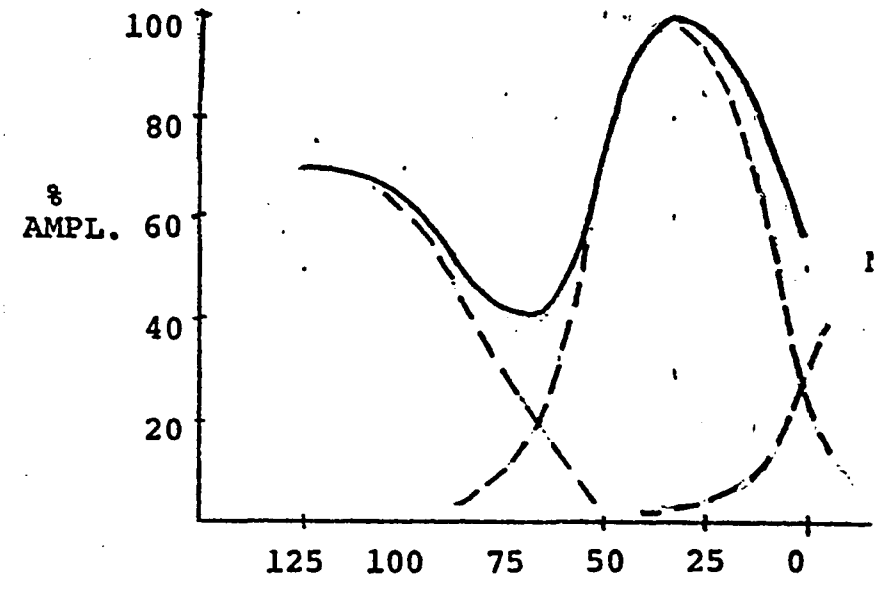
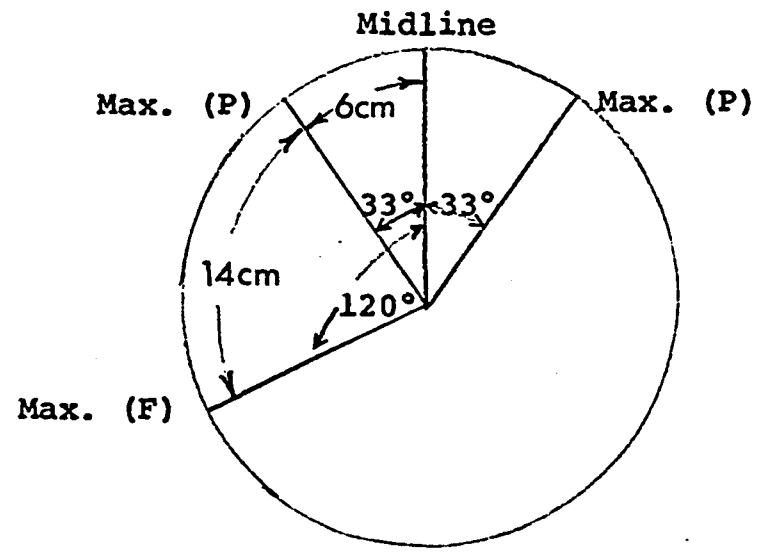


Figure 18: Field distributions computed from a volume conduction model of potentials generated by surface cortical sources. All curves are scaled to the same maximum amplitude. The curves represent sources of varying angular extent (6° , 12° , 24° , 48° , 72° , 96° , 120° , and 180°).

(Taken from Vaughan, 1973)

antecedent potentials is depicted in Figure 19. Similar operations were performed to define the frontal source.

Using these methods, the sources of the antecedent potentials for the three Ss were estimated (Figure 20).

Lambda Response

In the parieto-occipital region, potentials identified as the lambda response were seen following eye movements (Figure 21). All Ss displayed a positive deflection with mean peak latencies of 80 (RS), 110 (JK), and 120 (WR) msec from the onset of eye movement. This component was prominent in two Ss (JK and WR) and small in the other (RS). The later components of the lambda response were more variable across Ss. Although all Ss showed a subsequent positive deflection, it was not as clearly defined and consistent in its morphology across runs as the initial positive component. Mean peak latencies for the second positive wave were 200 msec for RS, 250 msec for WR and 350 msec for JK. A well-defined negative deflection following the first positive wave was seen in two Ss respectively, and a less consistent negative component at 170 msec was seen in WR.

Comparison with VER

The visual evoked response (VER) to a shift of the grating pattern (the same field as employed in condition [a]) is depicted in Figure 22 for the three Ss. An initial positive deflection occurred in all Ss of comparable latency to the initial positive component of the lambda response. It occurred at a mean peak latency of 105 (WR) and 120 (RS and JK)

**Figure 19: Posterior source of the antecedent potentials
for subject JK.**

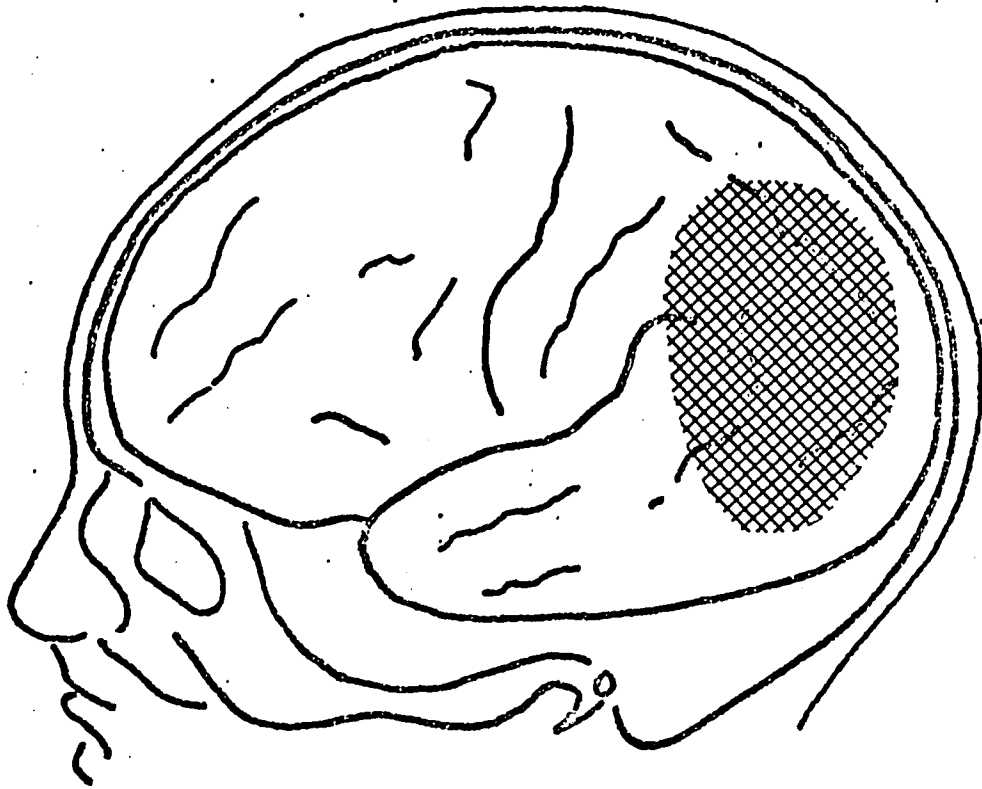


Figure 20: Sources of the antecedent potentials.

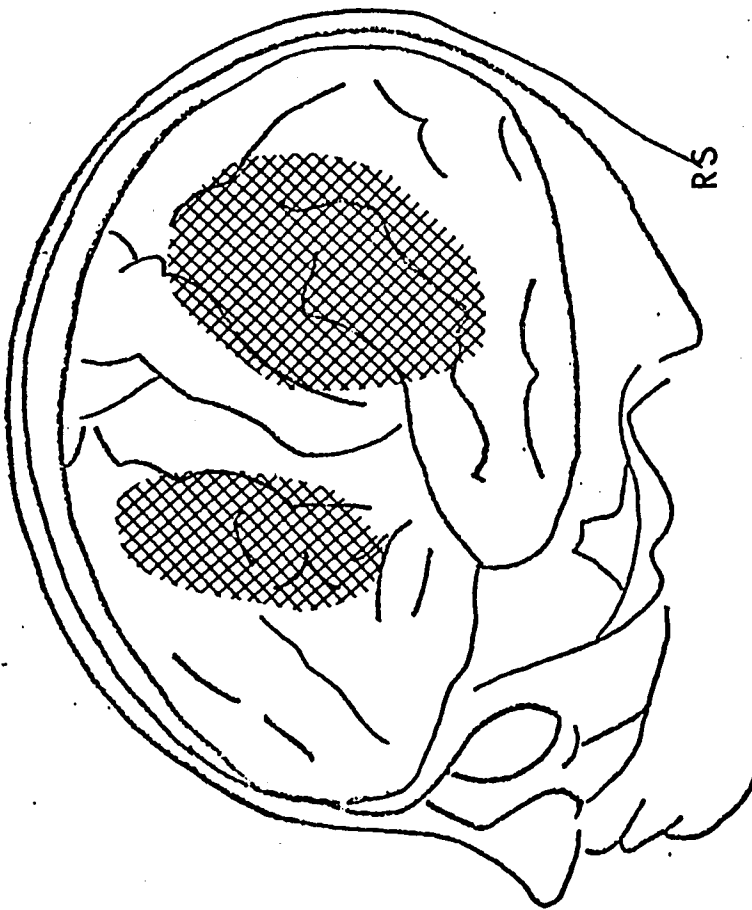
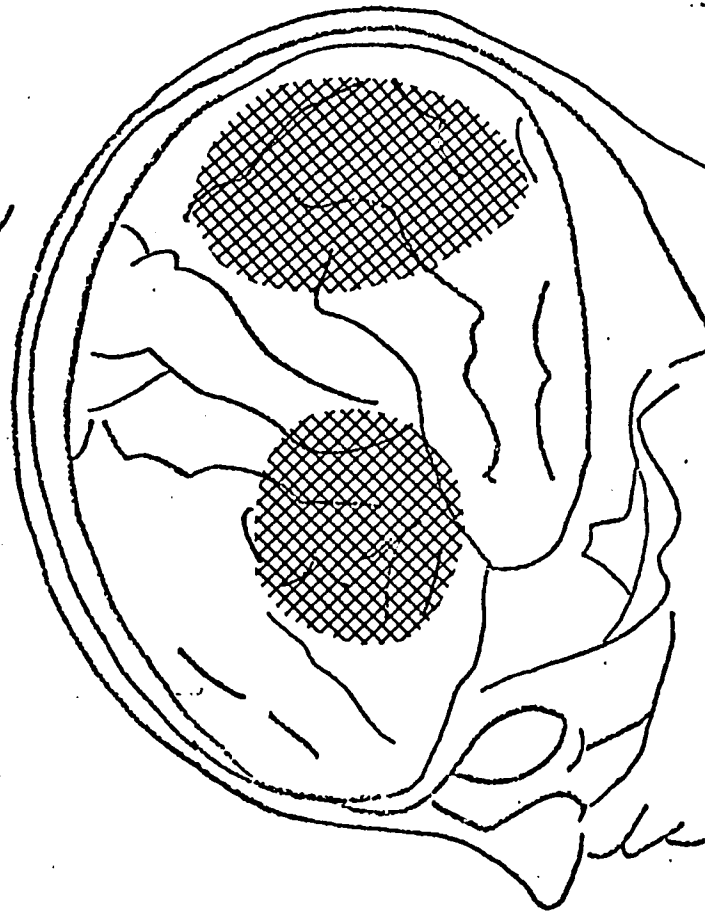
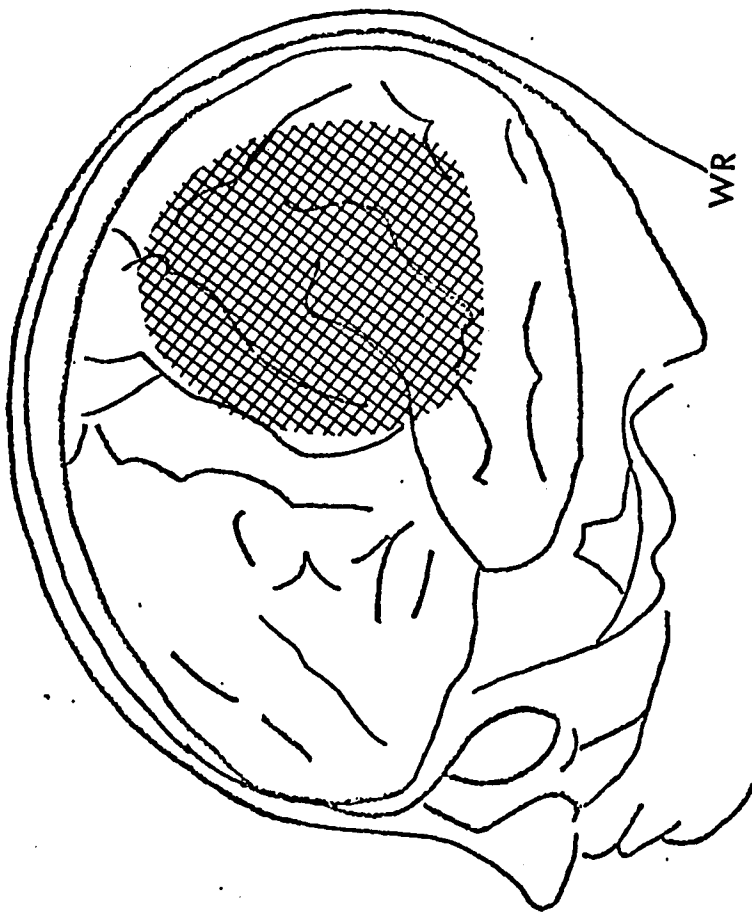


Figure 21: Potentials associated with 200 eye movements across the grating, recorded at the mid-occipital electrode (Oz) referred to linked ears. The lambda response begins after eye movement onset.

Subjects: JK, RS, WR

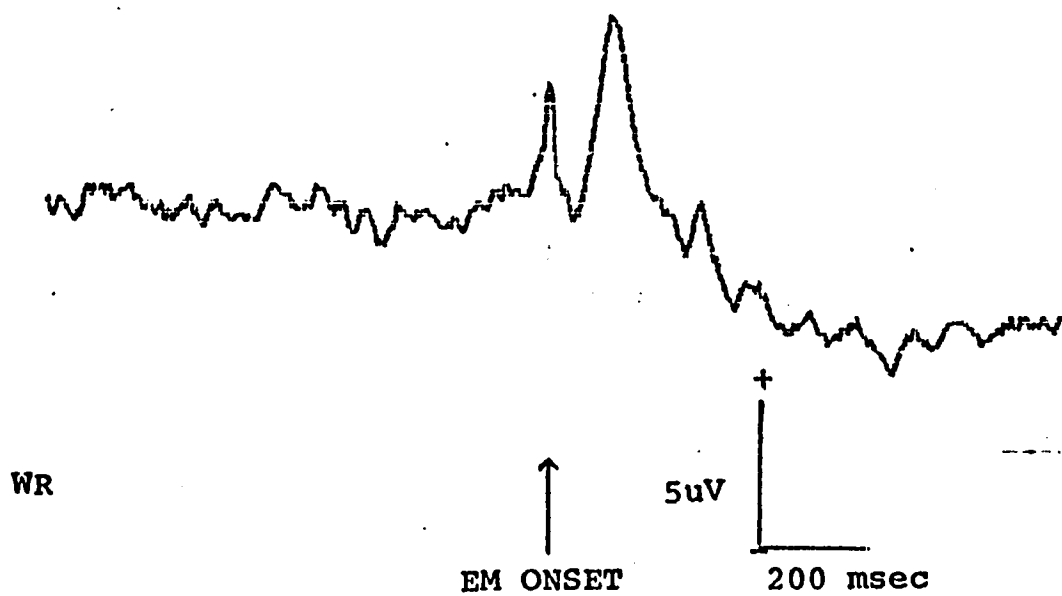
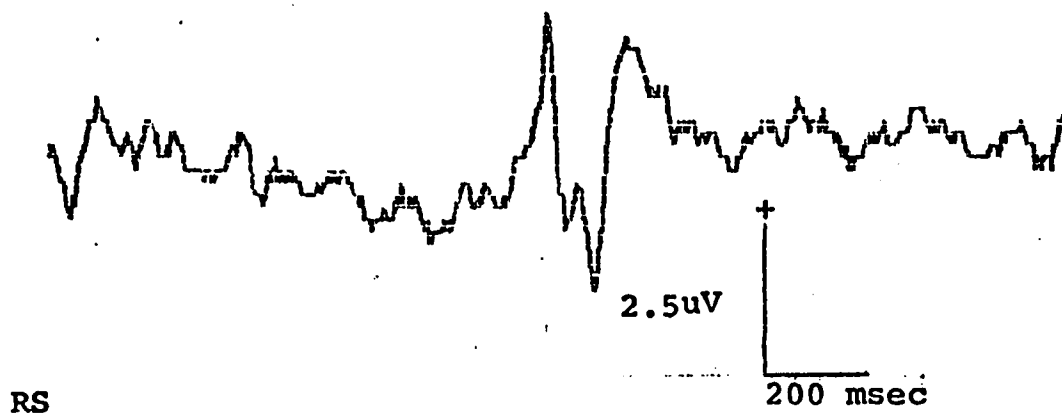
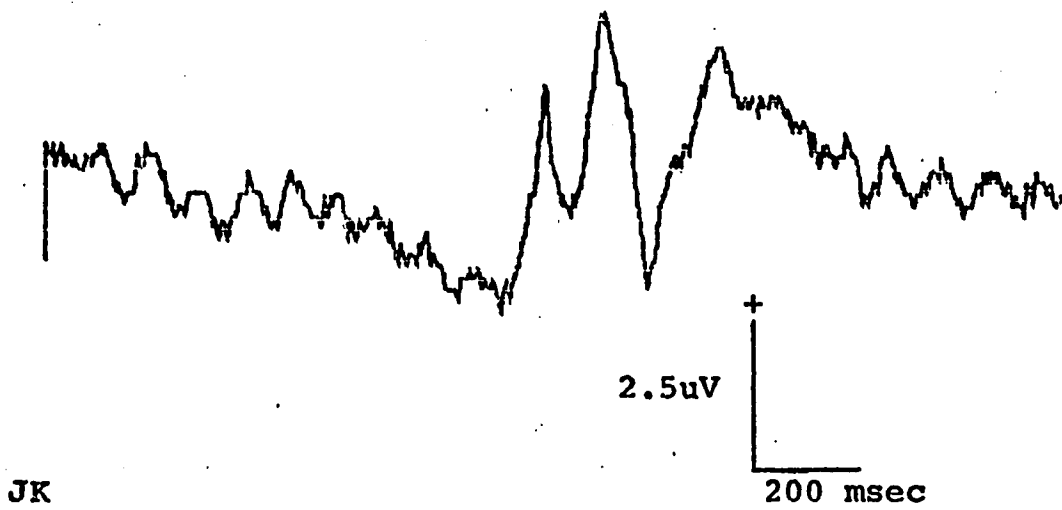
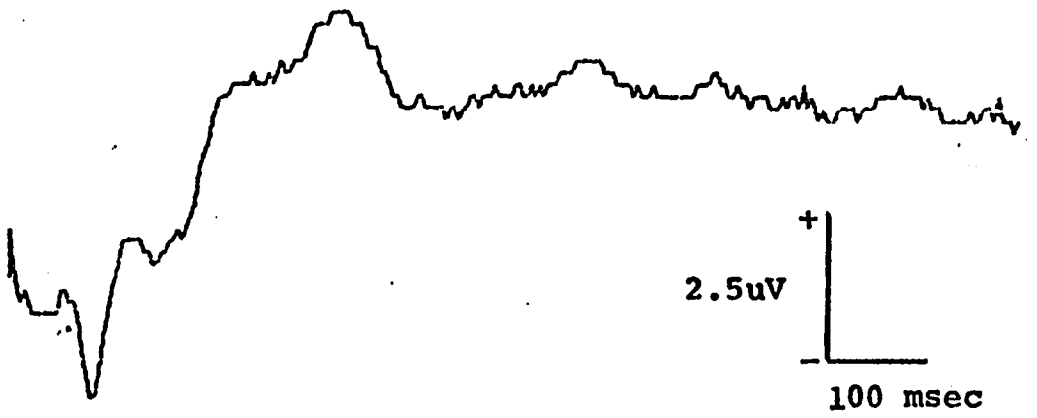
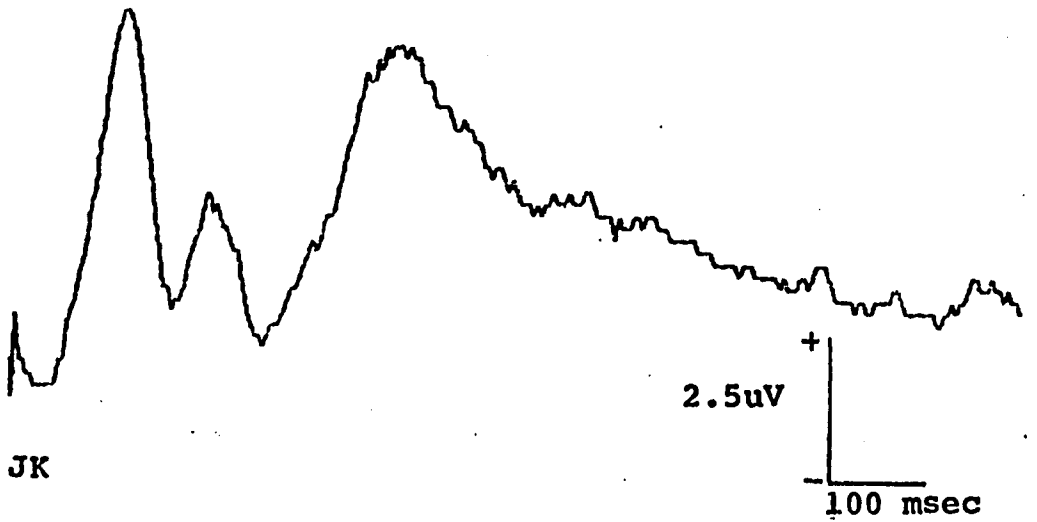


Figure 22: Visual evoked responses recorded from mid-occipital electrode (Oz) to the shift of the grating pattern. Pattern shift occurs at the onset of the trace.

Reference: Linked ears

Subjects: JK, RS, WR

Each average comprises 200 trials



msec after shift of the pattern. WR and JK, both of whom displayed a prominent initial positive deflection in the lambda response, showed a similar early positive component in the VER. For S RS, the initial component was small for both potentials.

A negative deflection followed this initial positive component with a mean peak latency of 120 (WR), 170 (RS) and 180 (JK) msec after shift of the pattern. This wave is comparable to the negative component of the lambda response.

A second positive component occurred at a mean peak latency of 220 (JK), 225 (WR) and 240 (RS) msec after pattern shift which was similar to the second positive component of the lambda response.

A second negative component occurring at 280 (WR and JK) and 290 (RS) msec was followed by a third positive deflection for RS and JK only at 360 and 400 msec respectively. This late positive component was absent for WR.

Experimental condition (a) was repeated with a 100-fold reduction in luminance of the stimulus field for JK. This resulted in decreased amplitude and longer latency for both the lambda response and the VER to the pattern shift (Figure 23). Mean peak latency for the initial positive component of the lambda response was 200 msec after initiation of the saccade and for the VER, 165 msec after the pattern shift. The succeeding negative component appeared at a latency of 300 msec for the lambda response and 220 msec for the VER.

Figure 23: A. Lambda response associated with eye movements over the grating under the standard illumination of condition (a) or the high luminance (H.L.) condition.

B. VER to pattern shift under the high luminance condition.

C. Same as A under condition of low luminance (L.L.), with field luminance reduced 100-fold.

D. Same as B, under low luminance condition.

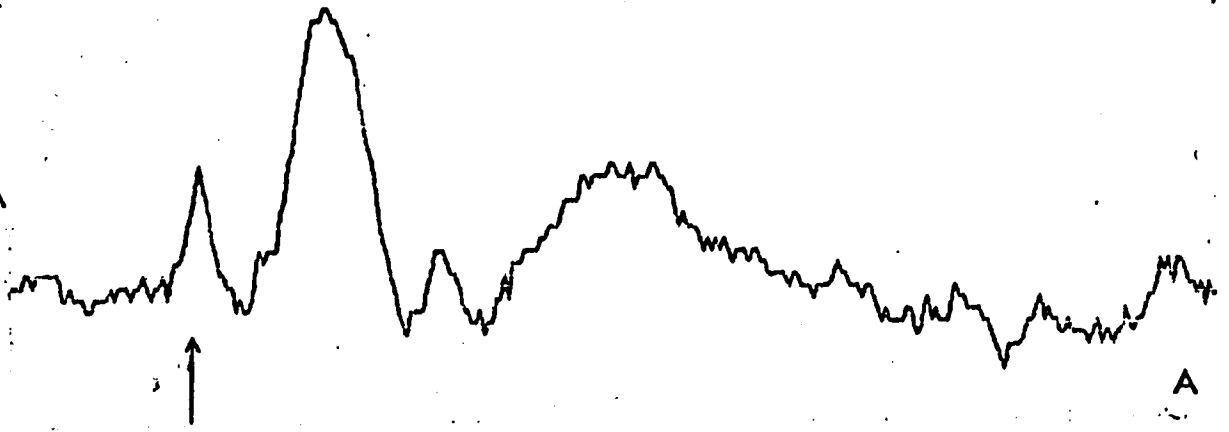
Eye Movement onset at arrow for A and C.

Pattern shift occurs at onset of trace for B and D.

Each average comprises 200 trials.

Electrode placement: Oz referred to linked ears.

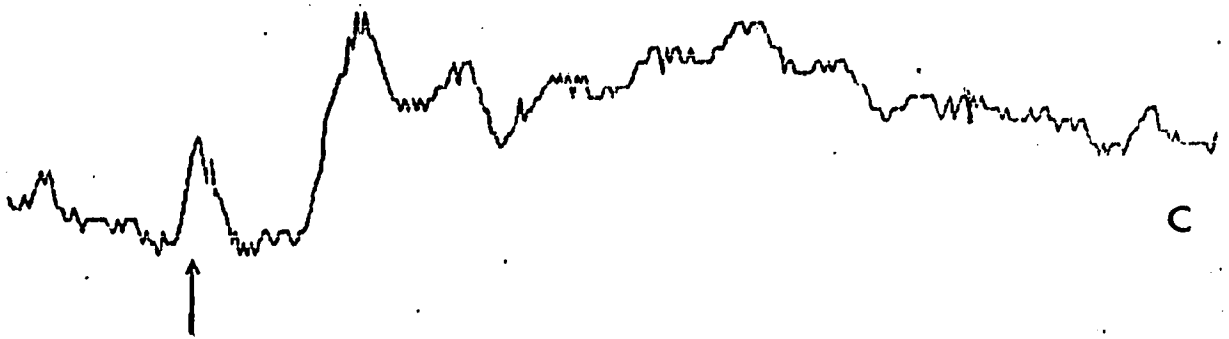
LAMBDA
H.L.



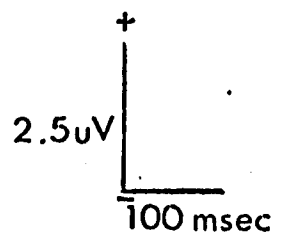
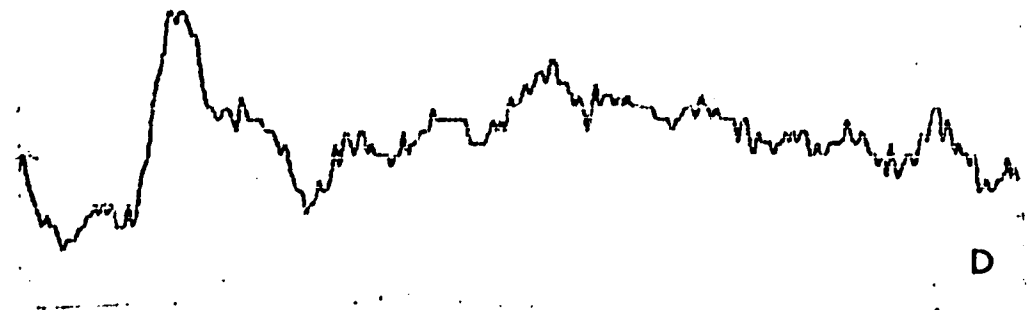
VER
H.L.



LAMBDA
L.L.



VER
L.L.



Both the VER and the lambda response showed an additional positive-negative complex. A comparison of the low luminance condition with the standard illumination of condition (a) is depicted in Figure 23 for both the lambda response and the VER. Both responses vary in the same manner to the reduction in field luminance, with diminution of amplitude and increase of latency of the initial positive wave.

The scalp distributions of the initial positive components of the lambda response and the VER were similar. Isopotential maps depicting these distributions for the three Ss are illustrated in Figures 24 and 25. All Ss showed maximum amplitude of the two potentials over the occipital region. In addition, WR displayed a second focus for the VER, overlying the central region. The occipital cortex is the source for both lambda response and the initial positive component of the VER inferred from application of the volume conduction model (Figures 26 and 27).

In summary, both the lambda response and the VER to a shift of the same pattern over which the eye movements were made displayed initial positive components, followed by a negative-positive complex. Both responses varied in a similar manner to a reduction in field luminance, with decrease in amplitude and increase in the latency of both the initial positive and subsequent negative waves. The scalp distributions of both lambda response and VER were similar, with occipital cortex the presumed source.

Figure 24: Isopotential maps for the initial positive component of the lambda response.

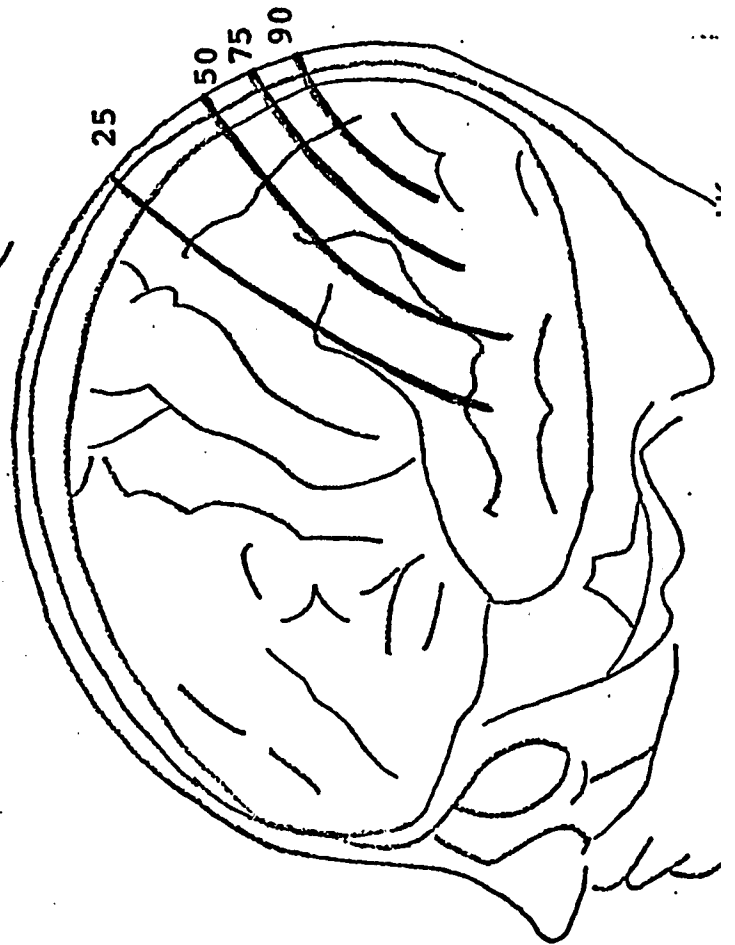
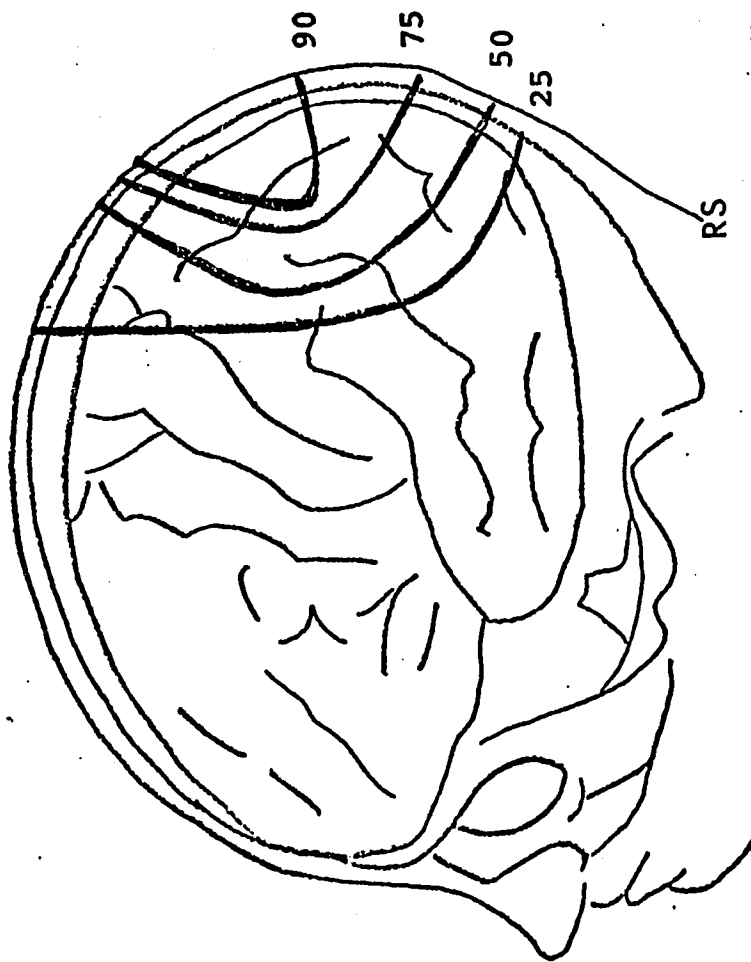
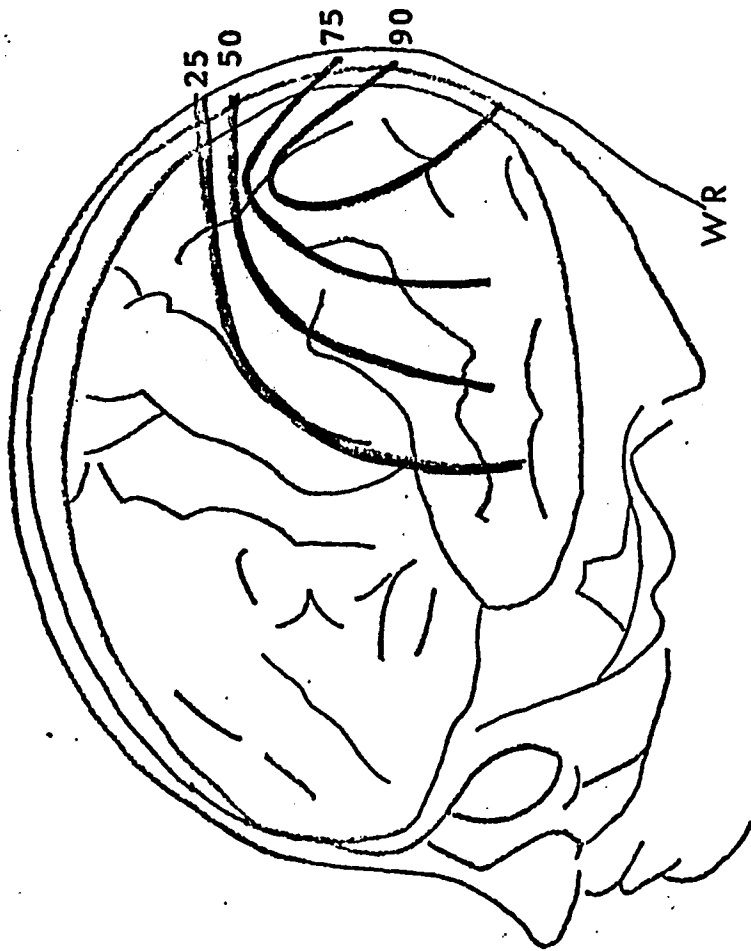


Figure 25: Isopotential maps for the initial positive component of the visual evoked response to shift of the grating.

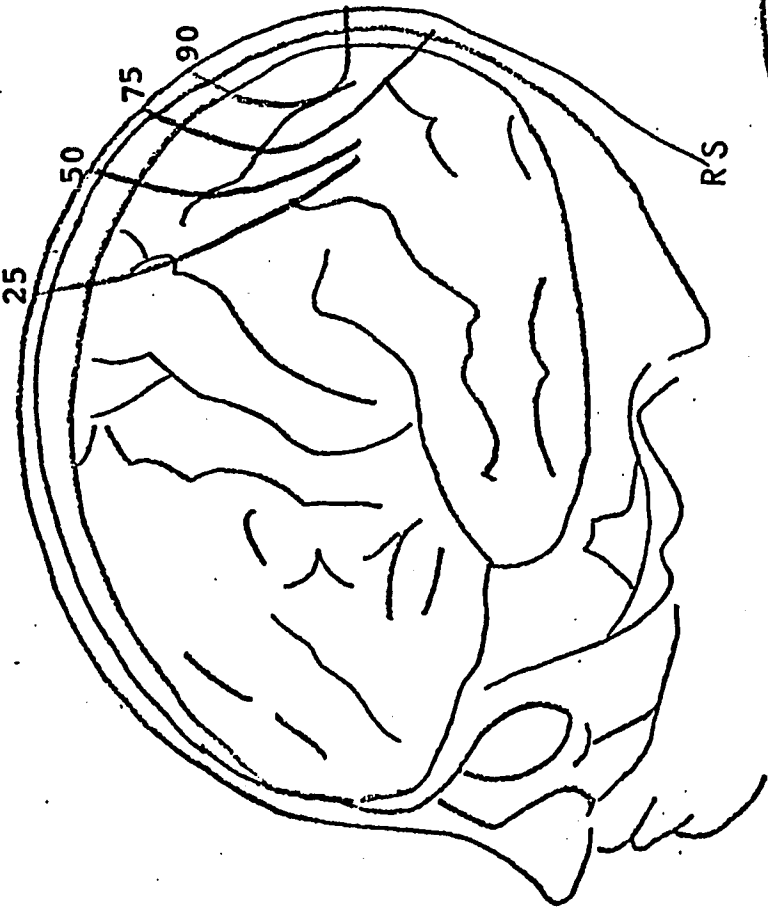
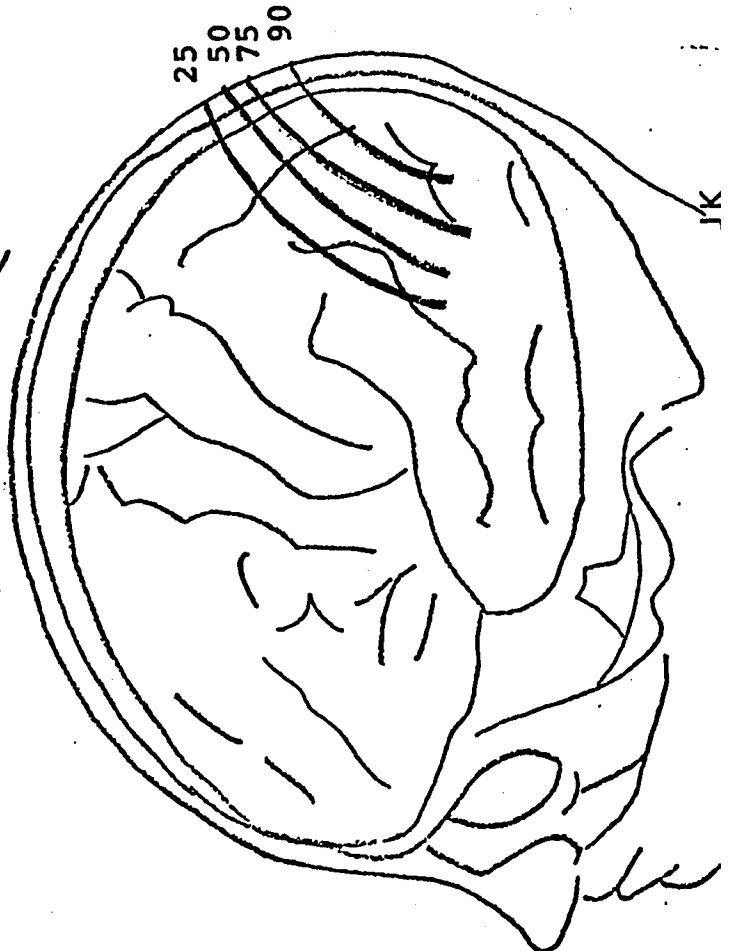
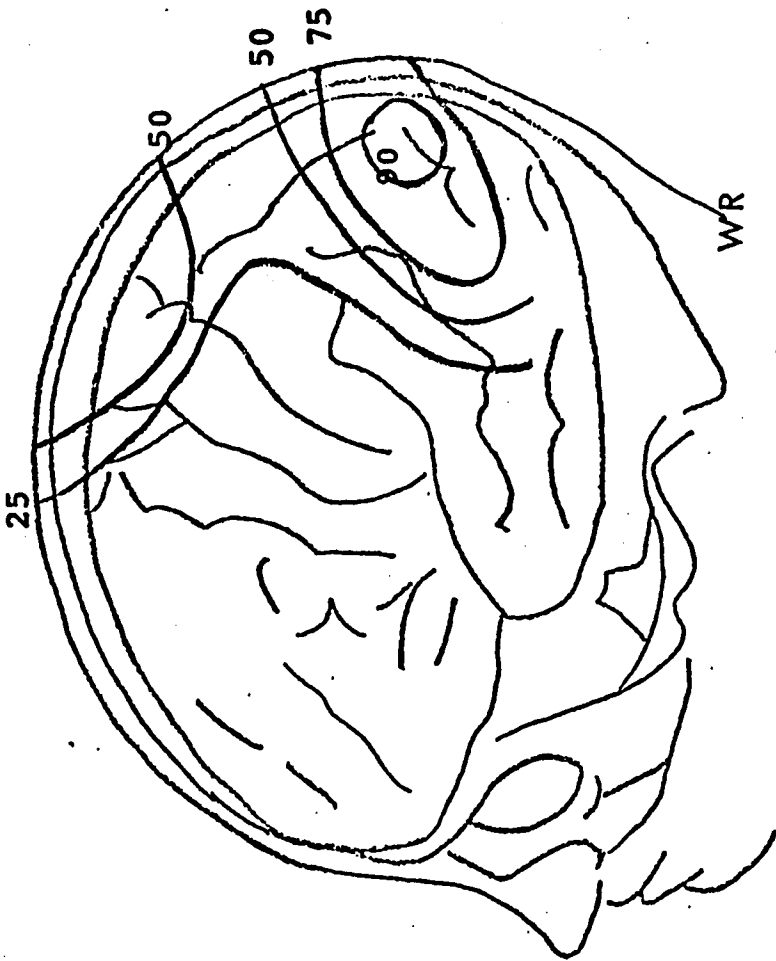


Figure 26: Sources of the initial positive component of the lambda response.

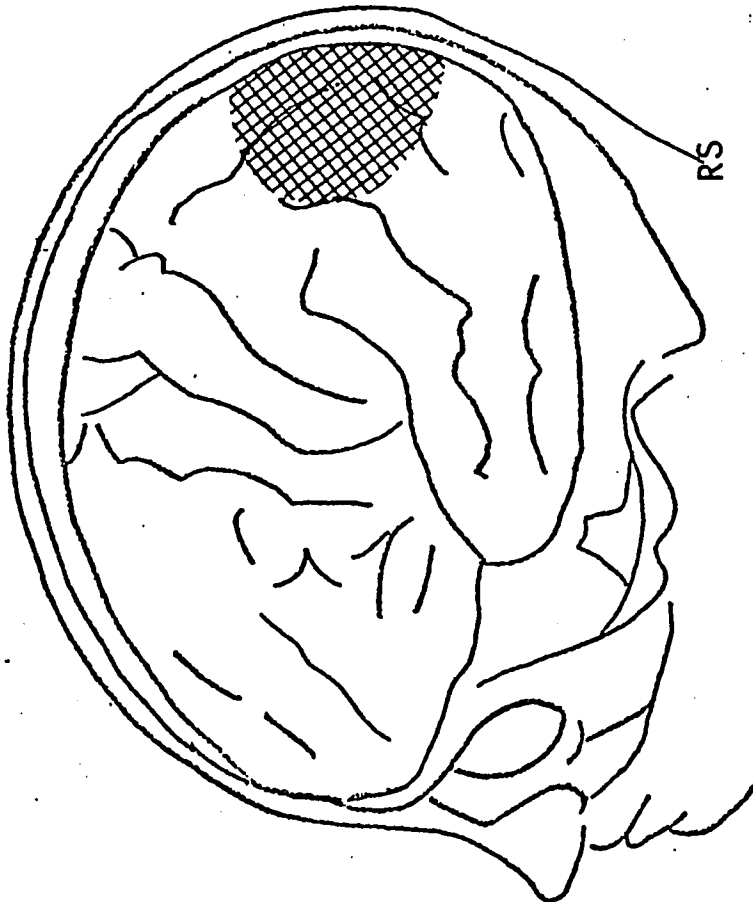
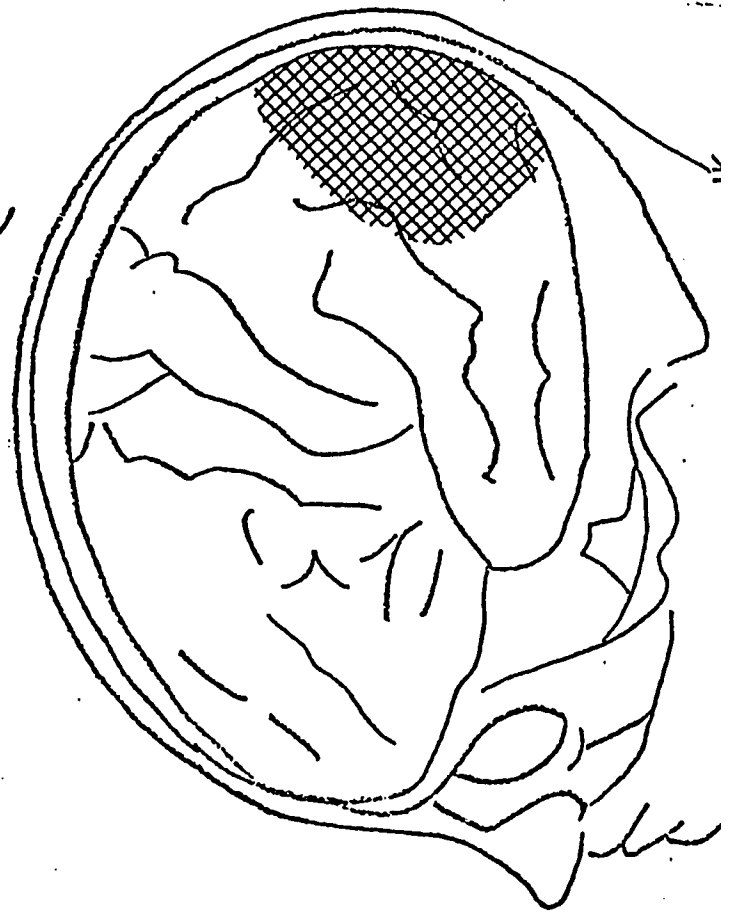
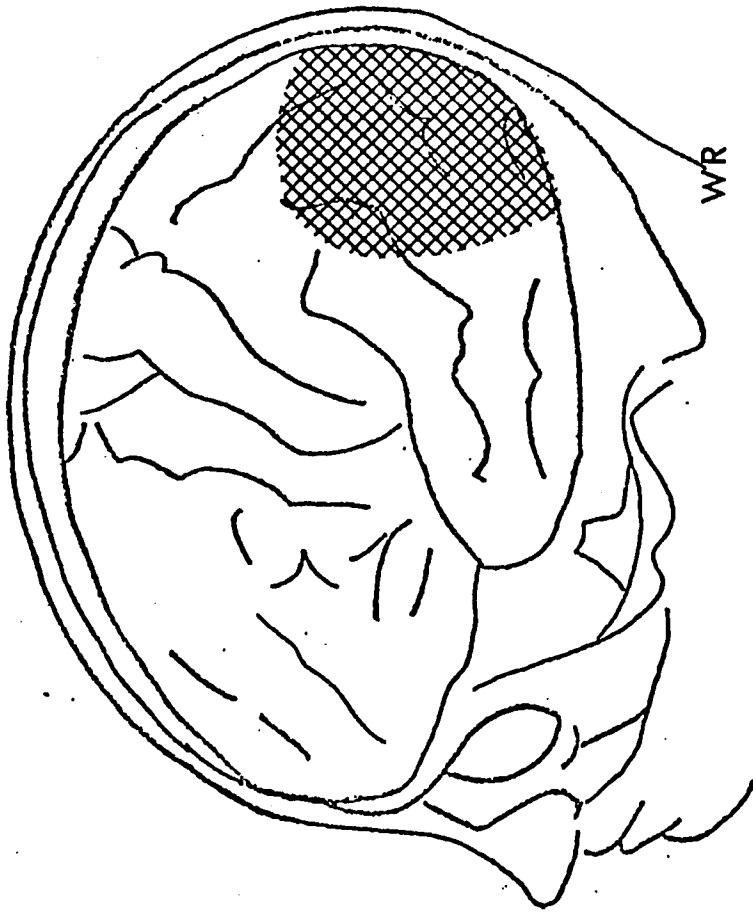
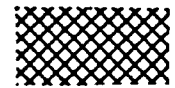
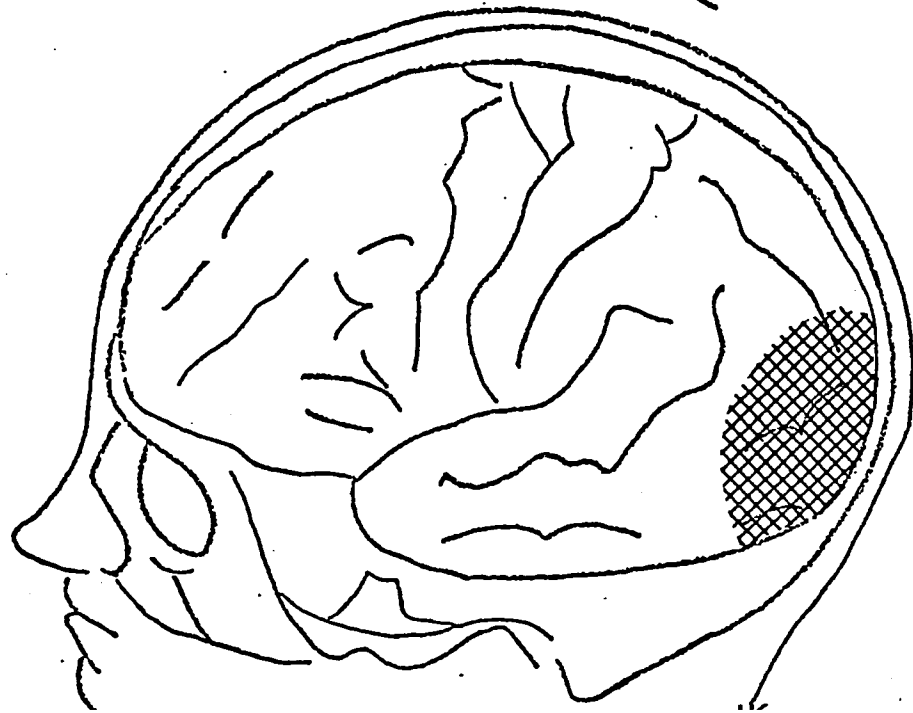
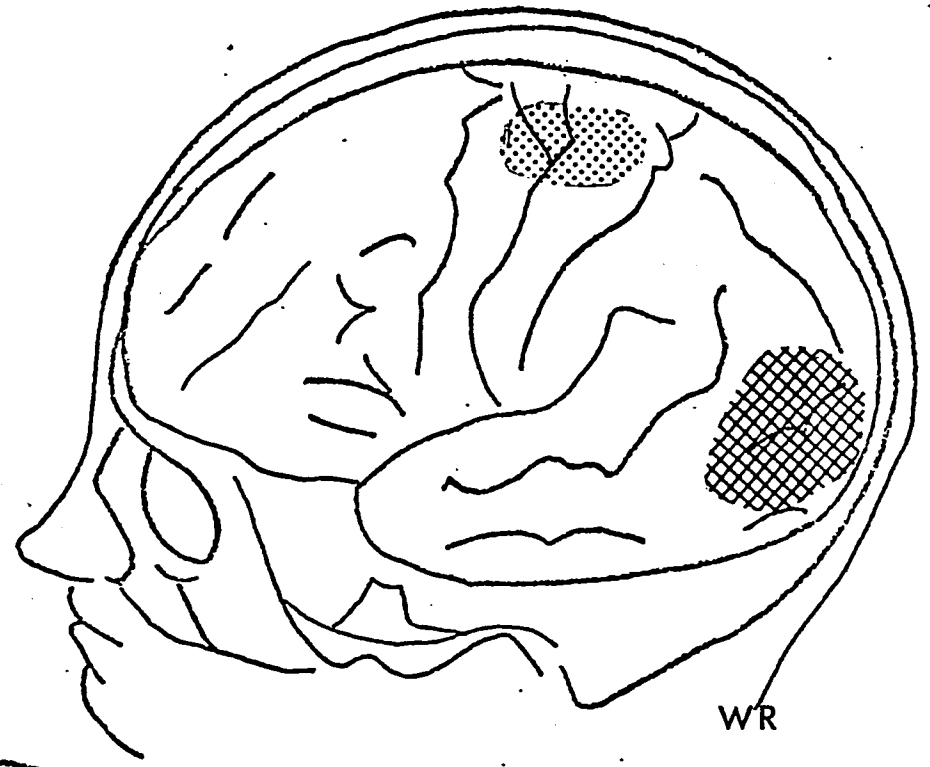
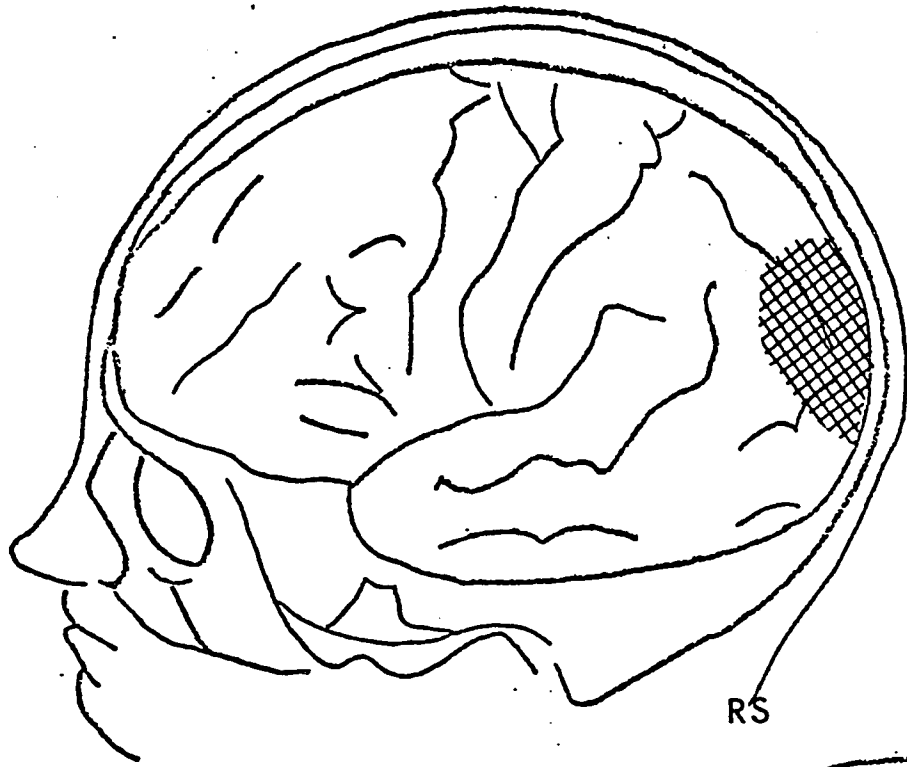
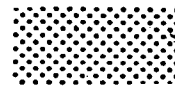


Figure 27: Sources of the initial positive component of the visual evoked response to shift of the grating. The secondary source depicted for subject WR represents an additional focus of lower amplitude activity as depicted in Figure 25.



PRIMARY



SECONDARY

Extracranial Potentials

Periorbital Activity

In the periorbital region, a distinct potential complex was recorded during horizontal saccadic eye movements (Figure 28). These potentials comprised a rapid-going negative-positive waveshape with supraorbital, suborbital, medial, and lateral leads displaying similar temporal and morphological characteristics. This activity showed consistent timing, with the first negative deflection beginning 5-10 msec prior to the onset of eye movement. Although EOG contamination was evident in the recordings from placements lateral and medial to the eye (Figure 29), the early portions of the phasic activity could be distinguished from the EOG since these occurred prior to eye movement initiation. The phasic periorbital potentials are thought to be distinct from activity related to the rotation of the eyeball (EOG) since their morphology remained basically alike with horizontal and vertical eye movements in either direction. If they were related to the EOG, the potentials would reverse in polarity with opposite direction of eye movement.

The distribution of the periorbital activity revealed a sharp decrement in amplitude with increasing distance from the eye, with a 50% reduction 5 cm from the center of the eyeball (see Figure 28).

Electrooculographic Distribution

The distribution along the scalp of potentials identified as conducted electrooculogram for eye movements

Figure 28: Potentials recorded from the periorbital region during 3° horizontal eye movements. Note common polarity and decrease in amplitude with distance from the orbit.

Reference: Linked ears

Subject: JK

Each trace represents 200 trials

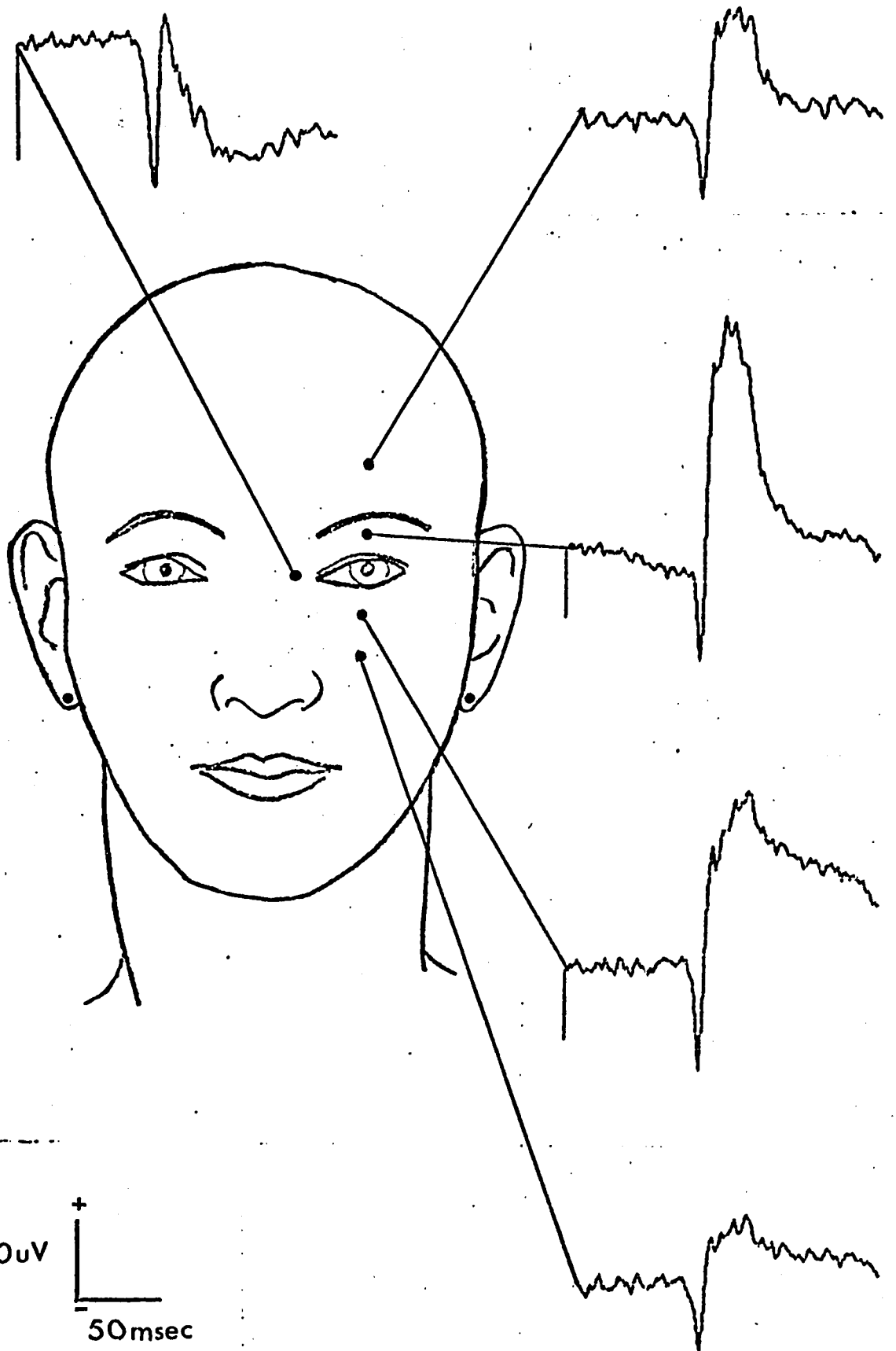
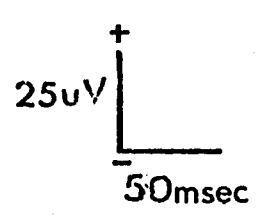
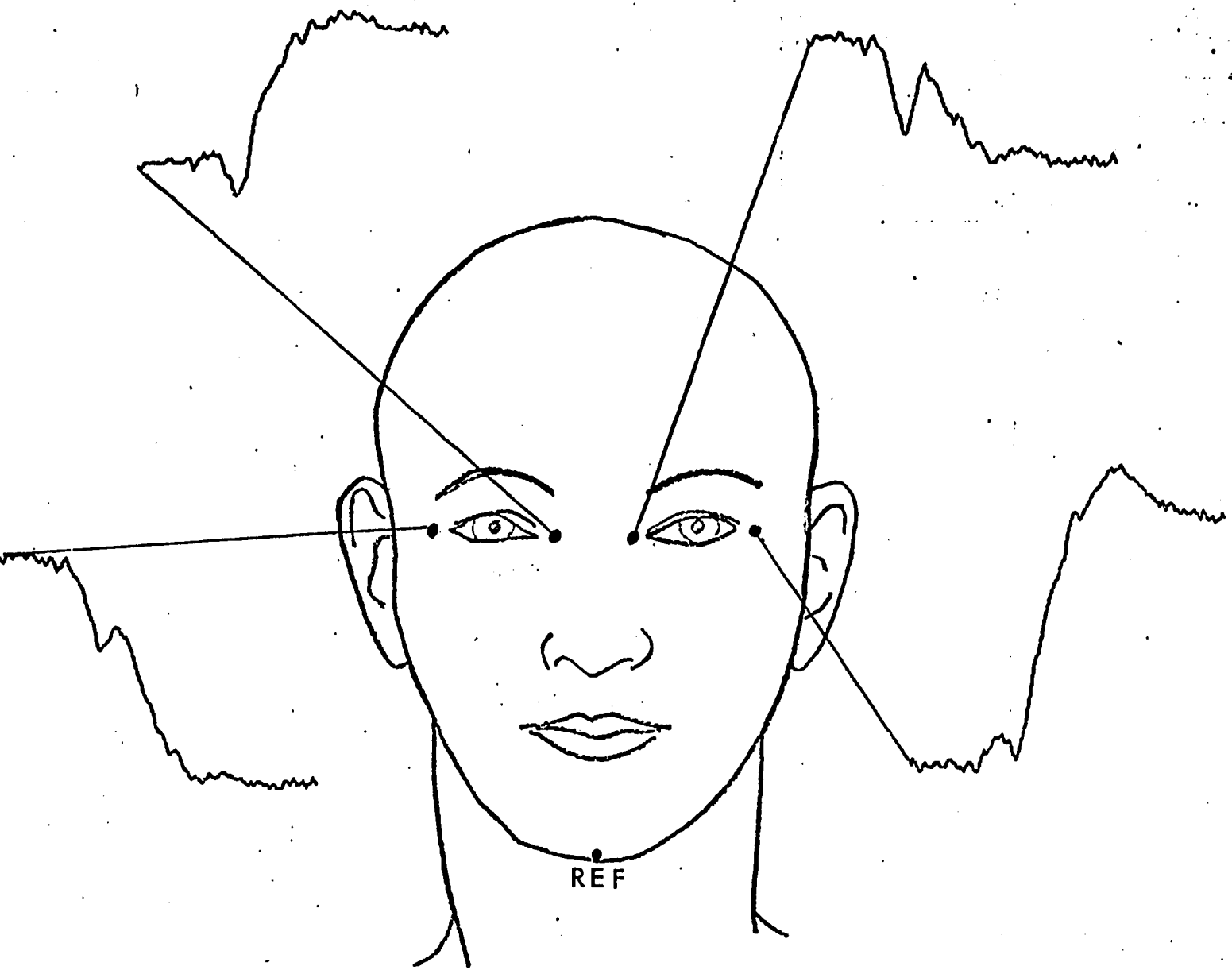


Figure 29: Periorbital potentials recorded from electrodes placed at the medial and lateral canthus of each eye during 7° horizontal eye movements. Note the initial negative-positive potential in all leads and the EOG which reverses in polarity across the eyeball.

Reference: Chin

Subject: JK

Average of 200 trials



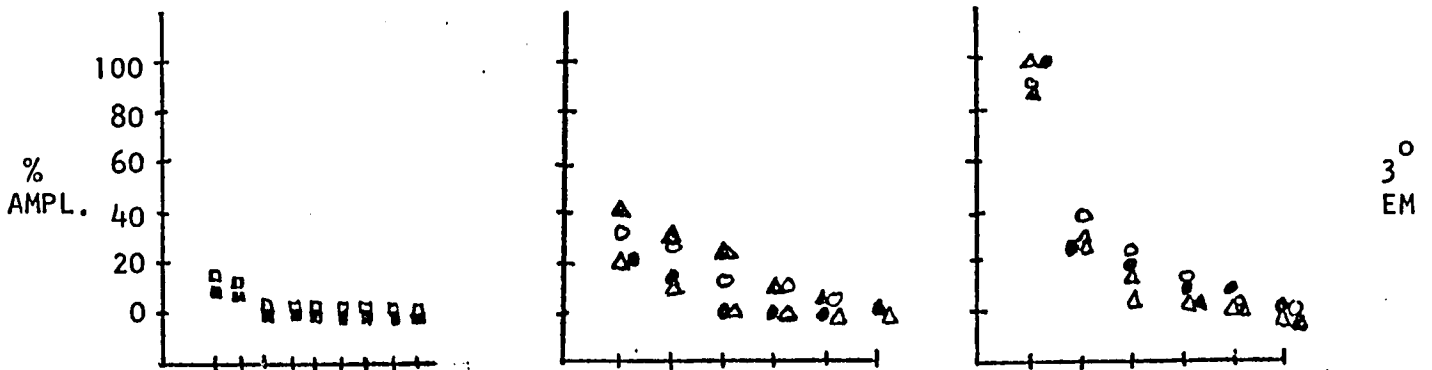
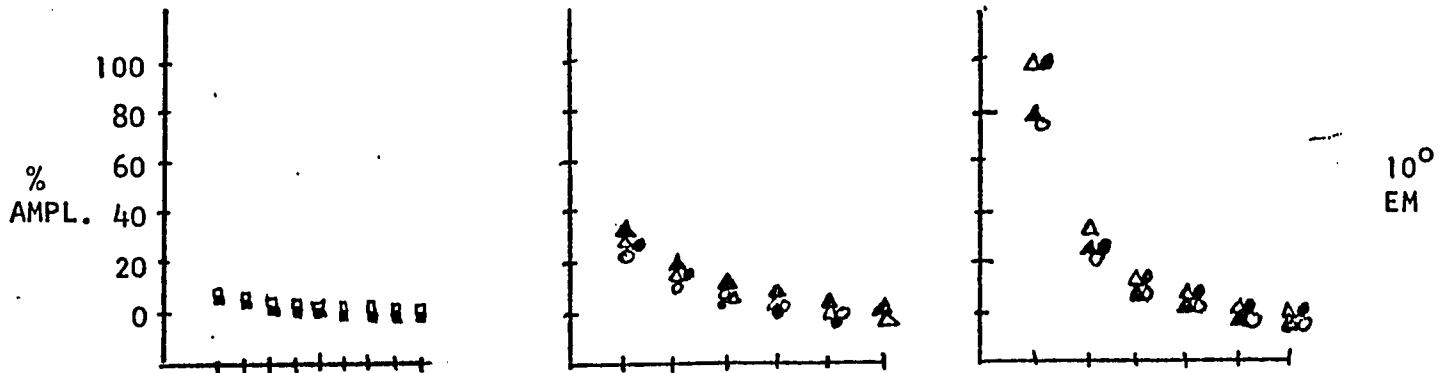
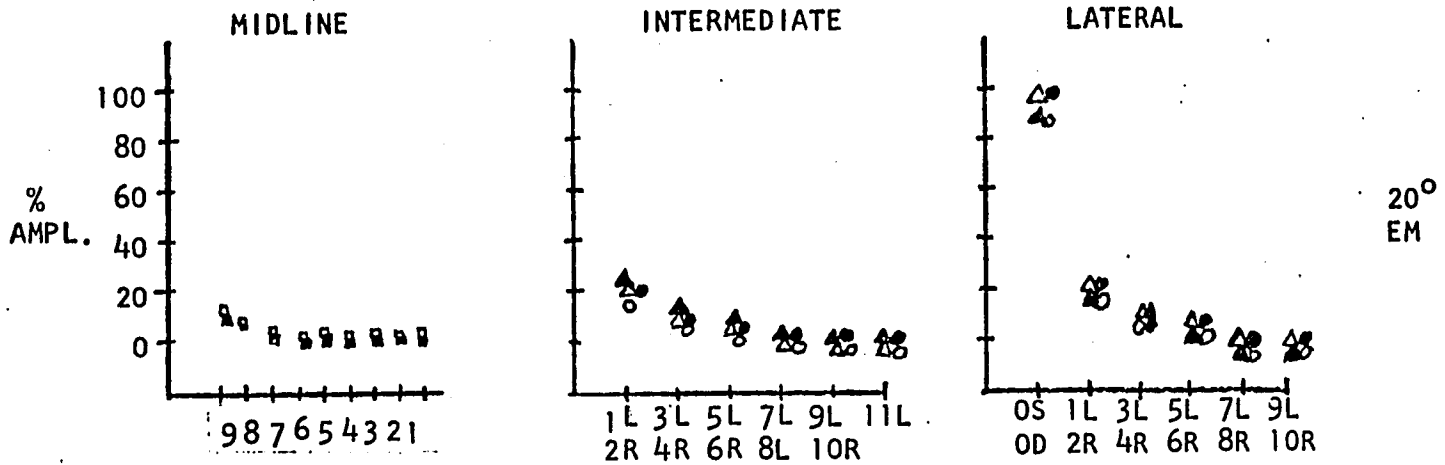
of 20°, 10°, and 3° is depicted in Figure 30. The measurements in microvolts of the amplitude of these potentials is given in Table I. The potentials were approximately equal and opposite in polarity for the two sides of the head with eye movements in either direction. That is, an ocular excursion from right to left was recorded as a positive deflection on the left side of the head, and a negative deflection of approximately equal amplitude on the right side. The distribution of the EOG recorded during the 3° saccade was slightly more variable because the amplitude of the conducted EOG for this small eye movement was not very large and therefore measurements were contaminated by brain potentials.

The distribution of the EOG is maximal in the orbital region and falls off rapidly with increasing distance from the eyes. The potentials are greatest in amplitude along the lateral chain and diminish toward the midline, with very little or no EOG detectable along the mid-sagittal line. This is illustrated in the isopotential map of Figure 31.

Neck Muscle Activity During Eye Movement

On-line visual inspection of electromyographic traces from right and left sternocleidomastoideus and splenium capitus muscles revealed no increase in activity during the performance of the eye movement task. Thus, the brain potentials recorded during these experiments appear to be exclusively due to ocular movements and not related to concurrent contractions of the neck muscles involved in rotation of the head.

Figure 30: Scalp distribution of the electrooculogram for eye movements of 20°, 10°, and 3° recorded from midline, intermediate, and lateral chains. Amplitudes are expressed as a percentage of the maximum value recorded at the lateral canthus for each ocular excursion (20°, 10°, and 3°).



- Midline array during R-L eye movement
- Midline array during L-R eye movement
- △ Left sided electrodes during R-L eye movement
- ▲ Left sided electrodes during L-R eye movement
- Right sided electrodes during R-L eye movement
- Right sided electrodes during L-R eye movement

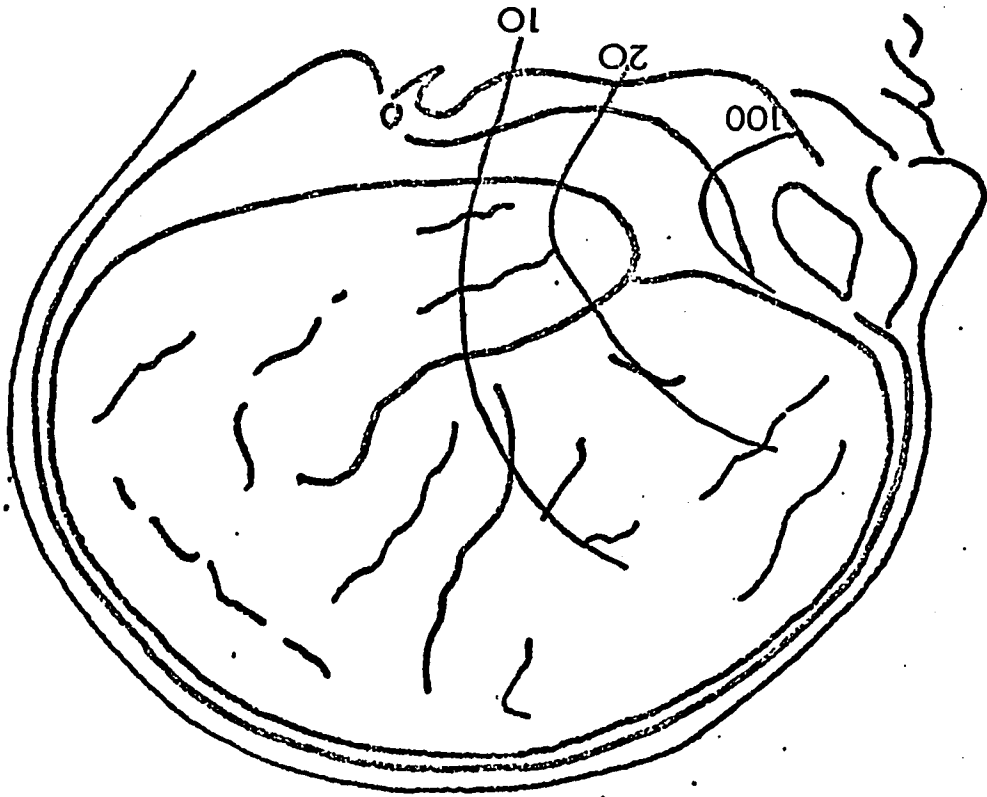
Table 1: Measurements of EOG amplitude represent the scalp potentials over the hemisphere toward which the eyes were moved (ipsiversive movements) as well as over the side of the head opposite to the direction of eye movement (contraversive movements) averaged for each of the two directions of movement and electrode arrays.

EOG DISTRIBUTION IN μV

	IPSIERSIVE MOVEMENTS			CONTRAVERSIVE MOVEMENTS		
	20°	10°	3°*	20°	10°	3°*
LATERAL						
OS,OD	225	111	37	198	88	43
1L,2R	51	34	14	48	30	16
3L,4R	22	16	6	27	18	10
5L,6R	10	7	1.9	14	10	5.4
7L,8R	8	4	2.5	6	3	0
9L,10R	4	2	0	5	1.5	0
INTERMEDIATE						
OS,OD	200	91	44	180	79	42
1L,2R	45	25	6.9	44	25	17.5
3L,4R	27	12	4.7	28	16	12.6
5L,6R	12	6	0	17	10	8.8
7L,8R	6	1.2	0	9	6	4.4
9L,10R	2	0	0	7	2.2	2.2

*The measurements of the 3° EOG distribution are less reliable than those of the 20° and 10° excursions due to the presence of brain potentials comparable in amplitude to the EOG.

Figure 31: Isopotential map for electrooculogram (EOG) associated with 20° eye movement.



CHAPTER IV

DISCUSSION

Antecedent Potentials

The slow potentials shifts (SPS) preceding the onset of eye movement by 500 msec or more are comparable to those recorded prior to other voluntary motor acts. SPS, called "readiness potentials", occurring prior to self-paced contractions of the extremities were described by Kornhuber and Deecke (1965) and Gilden, et al. (1966). These were interpreted as a manifestation of preparatory motor set. A subsequent investigation (Vaughan, et al, 1968) found the SPS preceding hand movements to be maximal overlying the central region contralateral to the contracting extremity. SPS have also been recorded in the absence of a motor response (Walter, 1967; Donald, 1970; Donchin, Gerbrandt, Leifer, and Tucker, 1972) when anticipation of an informative or signalling stimulus is part of the experimental design. This is the contingent negative variation ("CNV") of Walter and colleagues (1964). The relationship between the CNV and the readiness potential is as yet unclear. The recording and interpretation of SPS are also complicated by technical problems which include contamination by extra-cerebral sources such as EOG and skin potentials (Hillyard and Galambos, 1970; Picton and

Hillyard, 1972).

In the present experiments, SPS, which were most commonly negative, but occasionally positive in polarity, were not readily reproducible across runs. When the data were consistent over an entire montage, a rather widespread posterior-central distribution was found for the negative shift occurring before the saccades, which was similar to the distribution of the subsequent phasic antecedent potentials. Becker, Hoehne, Iwase, and Kornhuber (1972) in a similar experiment, reported a slightly greater amplitude of the SPS on the side contralateral to the direction of eye movement, with a maximal response overlying the vertex region. No consistent interhemispheric differences were found in the present experiments.

Although the SPS might have some functional significance in the production of the self-paced, voluntary eye movements performed under the experimental conditions employed in our work and that of Becker, et al., it is unlikely that these SPS reflect processes occurring during normal vision. Inasmuch as saccades occur two to four times per second, only a period of 250-500 msec is available to both register the visual information derived during a single fixation and to prepare for the next eye movement. Thus, activity recorded as much as 1000 msec before eye movement is not likely to be functionally significant under conditions of normal viewing. It is noteworthy, however, that the distribution of the SPS associated with the eye movements

was comparable to that of the phasic antecedent potentials. This suggests the involvement of these cortical regions in preparatory activity for saccades performed under the conditions of these experiments.

The phasic antecedent activity associated with horizontal saccadic eye movement began 60-190 msec before eye movement and displayed two sites of maximal activity -- the parieto-occipital and posterior frontal regions. Becker, et al. (1972) reported brain potentials associated with saccadic eye movements that were similar in morphology to those recorded in the present study. These authors also distinguished two components of the phasic antecedent potentials. The first slow positive deflection, termed the "pre-motion positivity", began 130-200 msec prior to saccades. The second component, the brief sharp positive deflection seen in our recordings at 10-30 msec prior to eye movement onset, was thought by Becker, et al. to represent volume conducted eye muscle potentials. In the present experiment, however, a similar distribution for the two antecedent components was found, with maxima in the parieto-occipital and posterior frontal regions, which would preclude an orbital source for these potentials.

Moreover, the analysis of the potentials recorded from the periorbital region revealed a temporally and spatially distinct set of potentials with a maximum amplitude near the eyeball, which declined sharply with distance from the

eye, reaching 50% amplitude 5 cm from the center of the eyeball. Similar activity was reported by Scott, et al. (1967) in conventional EEG recordings, which also showed a decrement with increasing distance from the eye.

It is possible that this activity represents activity of the extraocular musculature. The timing and morphology of the potentials recorded from supraorbital, suborbital, lateral and medial placements, however, are generally similar. If we were recording EMG from the extraocular muscles, the morphology of the potentials would vary depending upon which muscle was the agonist for a particular movement, with the antagonist showing inhibition during the eye movement (Miller, 1958). The only difference in morphology of the potentials recorded from medial and lateral placements appear to reflect EOG contamination since this part of the complex corresponded precisely in time with the EOG and reversed polarity with opposing direction of ocular movement (see Figure 29).

It is also possible that the periorbital activity represents compound nerve action potentials, since the onset of the first component occurred 5-10 msec prior to eye movement initiation as determined by the EOG. This is a comparable time course to the unit activity recorded in the oculomotor nuclei of alert monkeys. These units discharged approximately 2-10 msec prior to eye movement as defined by the EOG (Fuchs and Luschei, 1970; Robinson, 1970).

Further clarification of these periorbital potentials is necessary to more precisely define their nature. Nevertheless, it is clear that the sharp positive potentials, with maxima in the parieto-occipital and posterior frontal regions are distinct in morphology and timing from the activity that we have recorded periorbitally.

Comparisons of eye movement related potentials between the two hemispheres revealed no differences with movements in either direction. The results of bilateral stimulation (Mott and Schaefer, 1890; Sherrington, 1893) suggested that both hemispheres are active during the performance of eye movements. Recently, Mohler, Wurtz, and Goldberg (in press) recorded from FEF units in the alert monkey during the performance of visually initiated saccadic eye movements. All units related to eye movement (approximately 22% of the total number recorded) discharged after saccades to the contralateral side, and the majority of the same cells also responded after saccades to the ipsilateral side. This suggests that both FEF are active during saccadic eye movements in either direction. Since these units responded only after saccadic initiation, they may be functionally related to the internal monitoring of saccade magnitude and direction rather than saccade initiation. The possible role of the FEF in the eye movement control system is discussed below.

Comparison with Other Movement Related Potentials

At this point, the potentials associated with voluntary saccadic eye movement should be compared with the activity generated prior to voluntary movements of the extremities and

face. In these studies, the EEG is averaged with respect to the onset of muscle activity, as defined either electromyographically or mechanically (Kornhuber and Deecke, 1965; Gilden, et al., 1966). Although some discrepancies exist among investigations, the following brain potentials associated with voluntary movement have been most consistently described (Figure 32):

1. A slow negative shift beginning approximately one second prior to the onset of muscle contraction.
2. A sharp negative wave which precedes the contraction by varying amounts of time depending upon the particular muscle contracted as depicted in Figure 32. This negative component may be preceded by a small, but inconstant positive wave.
3. A large positive deflection which follows the contraction.

The topography of the motor potentials has been studied by Vaughan, et al. (1968), Deecke, Scheid, and Kornhuber (1969) and Gerbrandt, Goff, and Smith (1973). Although these studies vary somewhat in methods and in description of results, the pre-movement negativity has consistently been found to be maximal in amplitude overlying the central region contralateral to the muscle contraction. Vaughan, et al. (1968) reported a somatotopic distribution of both pre-movement negativity and the later positive component of the motor potential corresponding to the motor representation as defined by electrical stimulation (Penfield and Boldrey, 1937). Deecke, et al. (1969) reported a different distribution of the pre-movement positive component (termed "premotion positivity") that they believed is distinct

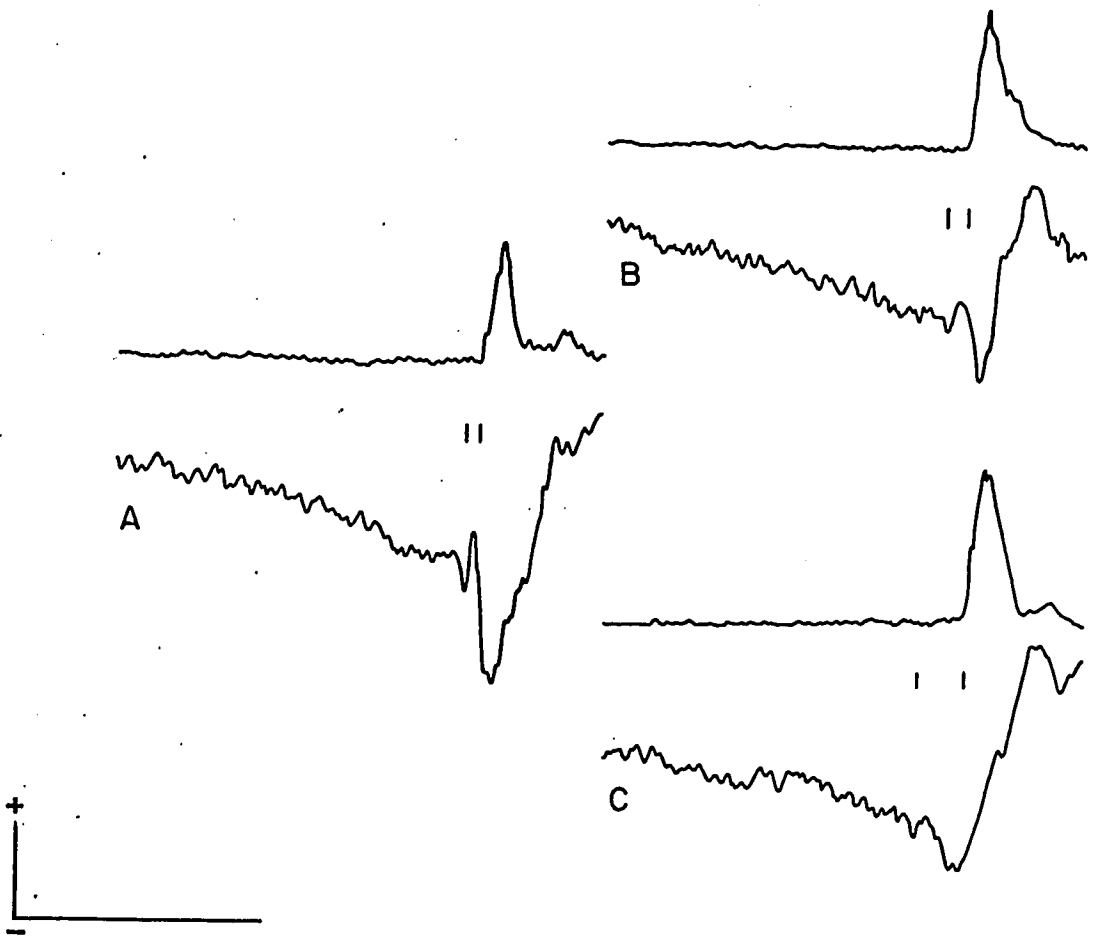
Figure 32: Rectified and averaged electromyograms (EMG) (upper trace) and averaged motor potentials (MP) (lower trace) for (A) unilateral lower facial contraction, (B) clenching fist, and (C) dorsiflexion of foot. Paired lines represent the onset of the sharp positive-negative component of the MP and the onset of the EMG. The incremental interval between the two reflect the variations in the length of the conduction path from the brain to the muscle contracted.

Calibration: A: 2.5 uV

B and C: 5 uV

Time Scale: 1 second

Taken from Vaughan, Costa, and Ritter, 1968.



from the pre-movement phasic negativity which they designate the "motor potential". The pre-movement positive component has been found by all workers, however, to be both small and inconstant within and across subjects, which makes it difficult to subject this component to a reliable topographic analysis.

The eye movement related antecedent potentials recorded in the present study differ in morphology and topography from the potentials associated with voluntary movement of the extremities. The slow negative shift seen invariably with activity preceding voluntary contractions of the extremities was not a consistent feature of the eye movement related potentials. The phasic antecedent potentials associated with saccadic eye movement are exclusively positive in polarity and have a clearly distinct topography from both the phasic negative component of the motor potential and the "premotion positivity" as described by Deecke, et al. Although Becker, et al. (1972) assert that the positive antecedent potentials associated with eye movements and the "premotion positivity" occurring prior to voluntary extremity movements are both maximal at the vertex, this is clearly refuted by the present more complete topographic study.

Despite the morphologic differences between the two pre-movement potentials, the timing of the eye movement related antecedent activity is consistent with the notion that both represent cortical activity associated with command signals. It is not yet clear if the morphologic differences reflect some underlying differences in cortical physiology, an issue which will be discussed subsequently.

Lambda Response and VER Comparison

The initial positive component of the lambda response, elicited when gaze was shifted across a grating, had strikingly similar temporal and spatial characteristics as the first component of the VER to a shift of the same pattern. Remond and Lesevre (1970) compared the spatio-temporal characteristics of the VER to a checkerboard displacement with the lambda response resulting from eye movements over the same checkerboard, and reported a close resemblance in waveform and topography between the two responses.

Both the alteration of the lambda response with diminished illumination (decreased amplitude, increased peak latency), also found by Gaarder, et al. (1964), and the observation that the lambda response was absent when eye movements were performed in the dark, in concurrence with the finding of Scott and Bickford (1969), support the notion that the lambda response is evoked by the displacement of the retinal image during eye movement.

Furthermore, it appears that the lambda response is mainly initiated at the onset of eye movement, rather than at its completion. The mean peak latencies of the first positive component of the lambda response and the VER are 103 msec after eye movement initiation and 117 msec after pattern shift respectively. Since the eye movement lasted for approximately 50 msec, the mean peak latency of the initial component of the lambda response would be only 53 msec if it were initiated at the completion

of the eye movement. Such a temporal disparity between the peak latency of the lambda response and the VER would run contrary to the otherwise comparable morphologic and topographic characteristics of the two responses, as well as to their similar behavior with alteration in stimulus intensity. Remond and Lesevre (1970) also believed that the early component of the lambda response is related to the onset of eye movement, whereas later portions of the response might reflect input at the termination of the eye movement. An apparently conflicting observation by Scott and Bickford (1969), who noted that a larger eye movement evoked a lambda response at a 20-40 msec increase in latency over a smaller eye movement, led them to conclude that the lambda response reflected the summing of visual input during scanning movements. The experimental conditions involving the two gaze displacements, however, were not comparable. For the large eye movement, Ss shifted gaze across a complex pattern between two fixation points placed at 24°. The smaller eye movements, called "free scanning" movements were made as Ss examined the stimulus material randomly. Thus, the differences in latency of the lambda response evoked by the large and small eye movements might be related to actual differences in the effective stimulus rather than to the size of the saccade.

Lesevre and Remond (1970) found that the fully developed lambda response was elicited by the presence of a patterned

field at the beginning of the eye movement, being unaffected by either its continued presence or absence during the remainder of the saccade. In addition, Gross, Vaughan, and Valenstein (1967), in studying the electrophysiological correlates of saccadic suppression, found only a small response to a test pattern presented during the eye movement, which further substantiates the lack of responsiveness of the visual system to changes in input during saccades.

Thus, it appears likely that the initial positive component of the lambda response is an evoked response to the onset of change in the retinal image caused by movement of the eyes across a patterned field, rather than a reflection of input occurring during the entire movement (as suggested by Scott and Bickford) or during the subsequent fixation. The functional interpretation of the lambda response will be further discussed in a subsequent section.

Functional Significance of Eye Movement Related Cortical Potentials

Interpretation of the brain potentials associated with saccadic eye movements must take into consideration the sensorimotor nature of the saccadic system. It is involved not only in the generation of an ocular movement, but in the reception and stabilization of the resulting visual input, and in the computation of the direction and amplitude of the next saccade. These computations are based upon an

integration of previous visual input with the "goal" of the eye movement (i.e., as in reading or examining an object). Thus, the saccadic system represents a closed loop or servomechanism, which incorporates the consequences of one eye movement to guide the subsequent movement.

Thus, we must take into consideration several functional characteristics of the system:

Under conditions of normal viewing, ocular fixation shifts from two to four times per second. Thus, the saccadic system has 250-500 msec after generating the motor command signal to process the inflow of visual information from the ensuing fixation and to determine the target of the next saccade.

These abrupt shifts in fixation result in a discontinuous input of visual information to the central visual system, but with no subjective awareness of this spatio-temporal discontinuity.

Furthermore, there is no subjective movement of the visual field corresponding to the movement of the image across the retina as the eyes actively change the point of fixation. Yet when the eyeball is moved passively or if there is an attempt to move the eyes by patients suffering from extraocular muscle paralysis (Kornmüller, 1931), subjective displacement of the visual scene is reported. Thus, there is a requirement for a "corollary discharge" (Sperry, 1950; Teuber, 1966) or "reafference" (von Holst and Mittelstaedt, 1950) to stabilize the visual field

during normal scanning which is inoperative during passive displacement of the eyeball but remains functional with muscular paralysis. Such a mechanism must therefore be closely related to the central motor command signal.

Thus, it should be possible to identify brain activity which is functionally related (1) to the motor command signal, (2) to the corollary discharge, (3) to the visual input both during eye movement and fixation, and (4) to the mechanism which encodes the direction and amplitude of the next eye movement. Although the task is a formidable one, requiring integration of the observations on cortical potentials with data from subcortical structures implicated in the system, it is possible to make some suggestions concerning the location and timing of the visuomotor processes within the cortex. The following is a discussion of the functional significance of the eye movement related potentials with respect to their spatiotemporal characteristics and their relationship to subcortical structures, as well as the specific functional characteristics of the saccadic system which seem to require representation at the cortical level.

It will first be necessary to consider the subcortical structures involved in the saccadic eye movement system and the anatomical relationships of the cortex to those structures. Although many subcortical structures have been associated with eye movement control (eg. cerebellum, vestibular system, portions of the thalamus); three major regions

have been most closely associated with visually guided saccadic eye movements. These are the superior colliculus (SC), the paramedian portion of the pontine reticular formation (PPRF), and the oculomotor nuclei, particularly (for horizontal movements) the third (oculomotor) and sixth (abducens) cranial nerves. Physiological evidence for the involvement of these structures in the saccadic eye movement system has been obtained through recording and stimulation experiments. A brief review of this evidence follows.

Superior Colliculus

Single unit activity occurring 10-150 msec (Wurtz and Goldberg, 1971); 70-500 msec (Schiller and Koerner, 1971); and 50-200 msec (Schiller and Stryker, 1972) prior to saccadic eye movement has been recorded in the deeper layers of the SC of the alert monkey. These eye movement related units fired in association with saccades of a specific size and direction irrespective of position of the eyes relative to the head. These data are supported by electrical stimulation studies of the deeper layers of the SC. In the alert monkey, Schiller and Stryker (1972) elicited conjugate saccadic eye movements of a constant direction, size and velocity, which were independent of initial eye position. The site of stimulation was the only determinant of amplitude and direction of the eye movement. These electrically elicited saccades precisely duplicated the spontaneous saccades as revealed by recording

techniques.

Robinson (1972) also elicited eye movements by SC stimulation with the same characteristics as Schiller and Stryker. He reported a 40-60 msec latency for saccades after stimulation with current near threshold. With current at twice threshold values, latency was reported as 30 msec. With five to ten times threshold current in the deeper layers of the SC, latency to eye movement was reported as 20 msec.

To summarize, the deeper layers of the SC possess properties similar to the frontal eye fields (as revealed by the stimulation study of Robinson and Fuchs) with respect to electrically elicited eye movements. That is, an eye movement of a specific amplitude and direction, irrespective of initial eye position, was elicited over a wide range of stimulus parameters. The only determinant of eye movement size and direction was the site of stimulation.

Pontine Reticular Formation

In the alert monkey, gross electrical activity was recorded from the medial portions of the nucleus Reticularis Magnocellularis, designated as the paramedian portion of the pontine reticular formation (PPRF) by Cohen and Feldman (1968). Potentials were found which preceded horizontal saccadic eye movements by 10-20 msec. In the rostral caudal portions of the PPRF, these potentials were larger and more complex when the eyes moved toward the ipsilateral side, whereas potentials recorded from the caudal ventral area were similar for eye movements in both

directions.

Single unit activity in the PPRF was investigated by Cohen and Henn (1972), who reported that nearly every unit they probed was related to saccades or to the quick phase of nystagmus, elicited by either visual or vestibular stimulation. The units showed no difference in activity whether associated with saccades or the quick phase of nystagmus. Most of the units altered their frequency of firing 12-20 msec before eye movement. This corresponds to the time course of the gross potentials recorded from the same structure. Two groups of units were described. One group increased firing frequency and the other was inhibited during eye movement. In addition, they found some units to be directionally specific, while others showed no difference in firing with direction of saccade.

Sparks and Travis (1971) distinguished three groups of units associated with horizontal eye movements in the mid-brain and pontine reticular formation of the alert monkey. Type I units changed their firing pattern with horizontal saccadic eye movements in either direction. Eleven out of thirteen of these units did not fire prior to saccade; two units increased their firing rate approximately 20 msec prior to eye movement. Type II units fired in association with either saccadic or smooth pursuit movements in a specific direction. Six of eleven units showed bursting 20-50 msec prior to horizontal saccades; the remaining five units increased their firing rate at the onset of

eye movement. Type III units showed spike bursts before saccadic eye movements of a specific direction and decreased frequency of firing during movements in the opposite direction. The change in firing frequency occurred 20 msec before saccades in five of eleven units, while six units showed simultaneous alteration in firing pattern with eye movement. This group seems to be similar to the units described by Cohen and Henn. All units which increased their firing rate prior to saccades in the Sparks and Travis study, were located in the pontine reticular formation.

The results of electrical stimulation of the PPRF support the recording data. Electrical stimulation of this region caused the eyes to move horizontally to the ipsilateral side (Cohen and Komatsuzaki, 1972). The amplitude of the eye movement was independent of eye position at the time of stimulation. The velocity of the eye movement was constant. In addition to saccadic eye movements, slow pursuit movements were obtained by altering the strength, frequency and duration of stimulation. Latency from stimulation to eye movement (defined by onset of EOG) was 5 msec and to activation of the contralateral medial rectus muscle was 2.3-3 msec.

Additional support for the involvement of the PPRF in mediating horizontal saccadic eye movements is obtained from studies describing the effects of experimental lesions to that area. Cohen and colleagues (Cohen, Komatsuzaki,

and Bender, 1968; Goebel, Komatsuzaki, Bender, and Cohen, 1971; Cohen and Henn, 1972) lesioned the PPRF in the monkey and reported ipsilateral horizontal gaze paralysis with the eyes fixed to the contralateral side. Vertical gaze was left intact. The recovery stage was characterized by paresis with eye movements of small amplitude and low velocity. In some cases, total paralysis remained.

Thus, the data from recording, stimulation, and lesions of the PPRF support the participation of this structure in the horizontal eye movement control system. From the latency data, it appears that the PPRF lies functionally close to the oculomotor nuclei.

Oculomotor Nuclei

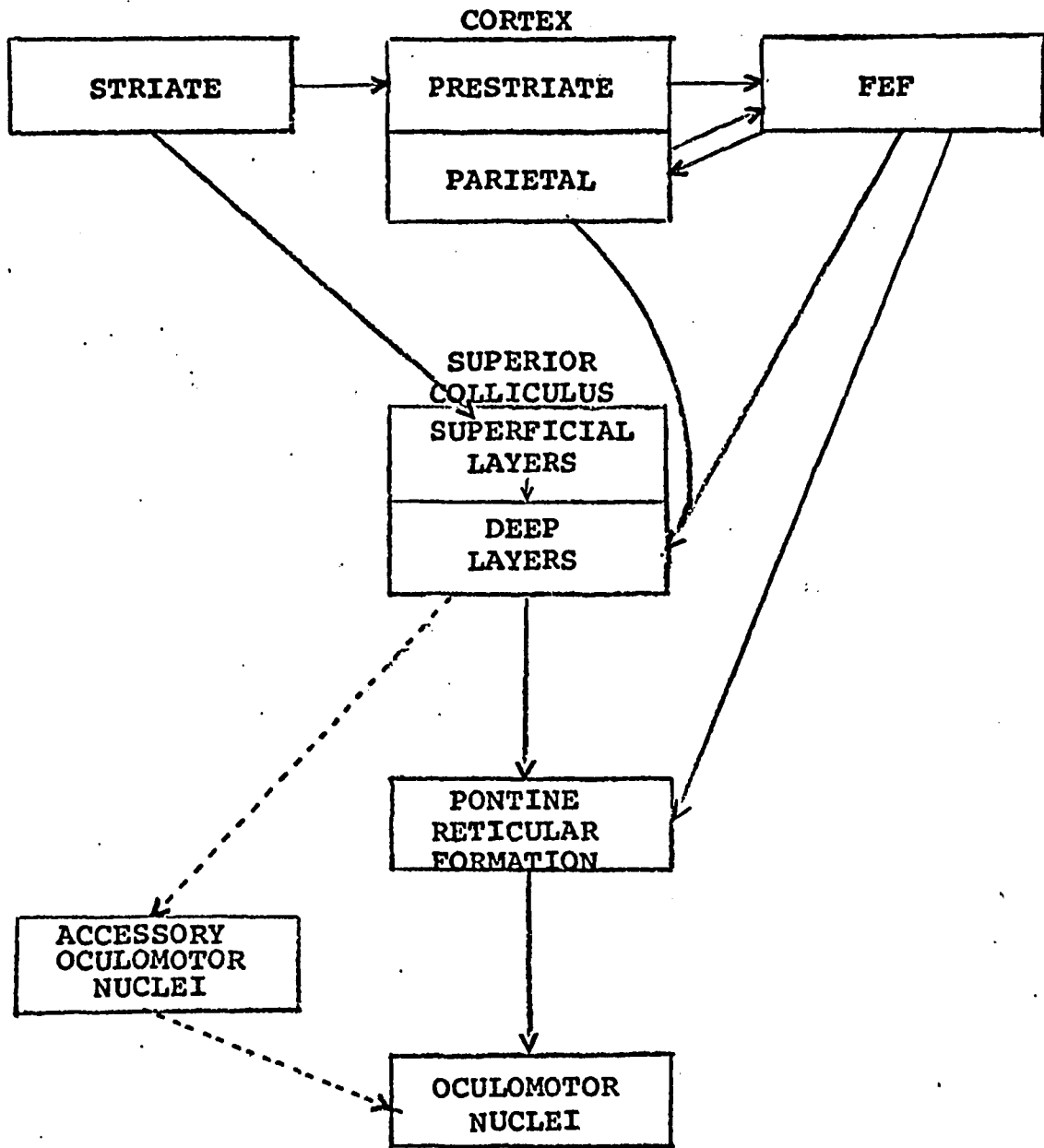
The final common pathway for the performance of all eye movements are the nuclei which innervate the extraocular musculature. In horizontal conjugate movements, the abducens and oculomotor nuclei, which innervate the lateral rectus and medial rectus muscles respectively, are concurrently activated. Fuchs and Luschei (1970) recorded unit activity in the abducens nucleus of the alert monkey. A total of 64 units were isolated, showing bursts of activity 1.8 - 11.4 msec before lateral saccades. Firing rate of these cells was inhibited prior to and during medial saccades. Robinson (1970) recorded from 35 units in the oculomotor nucleus of the alert monkey. With saccades in the on-direction, that is, the direction of action of the muscle involved, the units became active

4 - 10 msec before the beginning of the saccade. Inhibition of bursting activity preceded saccades in the off-direction by a similar time course.

The anatomical connections among these subcortical structures, and more particularly, their cortical afferents, provide further evidence for the functional saccadic eye movement pathway outlined above (Figure 33).

Abundant projections from arcuate cortex in the monkey (FEF) have been traced to the stratum lemnisci, stratum griseum superficiale and stratum opticum of the superior colliculus (Kuypers and Lawrence, 1967; Astruc, 1971). These are the same strata of the superior colliculus that contain units found to discharge prior to saccadic eye movements (Wurtz and Goldberg, 1971; Schiller and Koerner, 1971; Schiller and Stryker, 1972). Fibers from the area of the parietal lobe of the monkey found to elicit eye movements upon electrical stimulation (Ferrier, 1874; Fleming and Crosby, 1955) project to the same layers of the superior colliculus as does the FEF (Kuypers and Lawrence, 1967; Petras, 1971). Finally, occipital lobe projections to the superior colliculus terminate mainly in the superficial layers, including the stratum zonale, stratum opticum, and stratum griseum intermedium. These superficial layers of the superior colliculus are thought to project to its deeper layers (Kuypers and Lawrence, 1967). Thus, there is evidence for anatomical pathways from the cortical areas which have been implicated in

Figure 33: Anatomical connections among some cortical and subcortical structures implicated in the control of saccadic eye movements. Solid lines represent pathways disclosed by degeneration studies. Broken lines are hypothesized pathways.



oculomotor control to layers of the superior colliculus containing eye movement associated units.

Evidence based on degeneration studies of pathways leading from the superior colliculus indicates that there are no direct connections from the superior colliculus to the oculomotor nuclei of the cat (Altman and Carpenter, 1961; Carpenter, 1971) and the monkey (Myers, 1963). Carpenter suggested that the fibers from the superior colliculus could reach the extraocular muscle nuclei via the accessory oculomotor nuclei (Darkschewitsch and Cajal) or via the reticular formation. Lesions of the superior colliculus caused degeneration of these nuclei in the cat (Altman and Carpenter, 1961) and Myers (1963) traced a projection from the superior colliculus to the pontine reticular formation in the monkey. It should be noted that direct connections between the FEF and the pontine reticular formation have been found in the monkey by Kuypers and Lawrence (1967). Finally, the Scheibels (1958) and Carpenter and McMasters (1963) have traced projections from the pontine reticular formation to the oculomotor nuclei.

Thus, we have pathways from the cortical areas thought to be involved in the control of eye movements to the superior colliculus, and additionally, from the FEF to the pontine reticular formation. Pathways from the superior colliculus to the oculomotor nuclei remain undefined, but the evidence suggests that there are pathways from the

pontine reticular formation to the oculomotor nuclei.

Relationship Among FEF, PEF, and SC

Three major structures which may be implicated in the initiation and control of saccadic eye movements are the frontal eye fields, the parieto-occipital eye fields, and the superior colliculus. Yet ablation of any one structure does not lead to permanent dysfunction of saccadic eye movements. Indeed, ablation of the superior colliculus, the structure that is implicated in saccadic generation by the clearest physiological evidence, does not result in a gross alteration of visually guided eye movements (Pasik, Pasik, and Bender, 1966; Anderson and Symmes, 1969). Wurtz and Goldberg (1972) have, however, documented an increase in the reaction time for an eye movement to the onset of a visual stimulus in trained monkeys, which declined over a period of one to seven weeks after the lesion. Similarly, cortical ablations seem to produce rather mild and fleeting deficits of oculomotor function. Therefore, there must be some functional redundancy among the structures subserving eye movement control.

What are the relationships among these three structures? The SC and the FEF possess similar characteristics with respect to elicitation of saccadic eye movements by electrical stimulation (Robinson and Fuchs, 1969; Schiller and Stryker, 1972; Robinson, 1972). The evoked saccades are independent of initial eye position. The neurons of both structures appear to encode specific saccadic vectors; that is, eye

movements of a predetermined size and direction. Latency from stimulation to saccade as reported by Robinson and Fuchs for the FEF was usually 25 msec, and with the use of a stronger current, latency was reduced to 15 msec. For the SC, Robinson reported the shortest latency from stimulation to saccade as 20 msec. In addition, ablation of the SC does not alter saccades elicited through FEF stimulation (Schiller, 1972). From these data, it might be inferred that the FEF is able to operate independently from the SC, and despite the heavy projections from the FEF to the deeper eye movement related strata of the SC, some fibers carrying command signals must bypass the SC and go directly to the PPRF. Indeed, there are direct projections to the PPRF from both the SC and the FEF.

When we come to the results of recording electrical activity associated with eye movement, the findings of Bizzi for the FEF and Schiller and coworkers for the SC differ. Bizzi reported only two cells out of 102 eye movement related units in the FEF of the alert monkey fired prior to eye movement initiation. These observations were recently confirmed by Mohler, Goldberg and Wurtz (in press) who recorded from 137 FEF cells, 22% of which were eye movement related and discharged 30 msec after the onset of visually initiated saccades. An interesting observation was that the eye movement related cells discharged for longer durations and/or at a higher frequency after saccades of larger amplitude. The initial position of the eye had no

effect on the discharge characteristics of the cell. The authors suggested that perhaps these FEF cells encode information pertaining to the size of the saccade.

In contrast to these findings in the FEF, Schiller found many units in the deeper layers of the alert monkey's SC which fired before saccades. The discrepancy between the FEF and SC with respect to alteration of firing frequency of units prior to saccades in light of the similarities in electrically elicited saccades is puzzling. Although the negative data with respect to unit activity preceding eye movements have led Bizzi, and more recently, Mohler, et al. to discount the possible role of the FEF in the initiation of eye movements, these data seem inconsistent both with the short latency to eye movement from FEF stimulation and the lack of effect of SC lesions on electrically elicited saccades from FEF stimulation.

The relationship between the PEF and the subcortical components of the saccadic eye movement system is even less clear. Schiller (1972) reported that after SC ablations, electrical stimulation of the visual cortex failed to produce eye movements. He did not, however, stimulate the prestriate and posterior parietal regions. Additional experiments are needed in order to precisely define the oculomotor effects of PEF stimulation as has been done for the FEF and the SC.

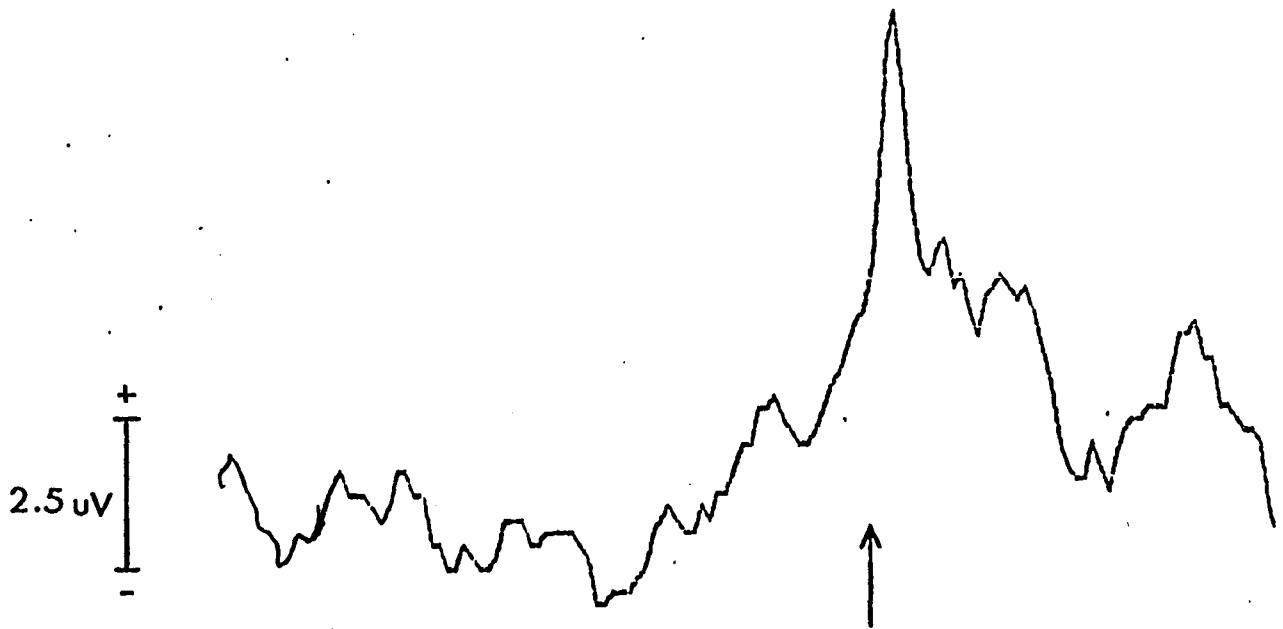
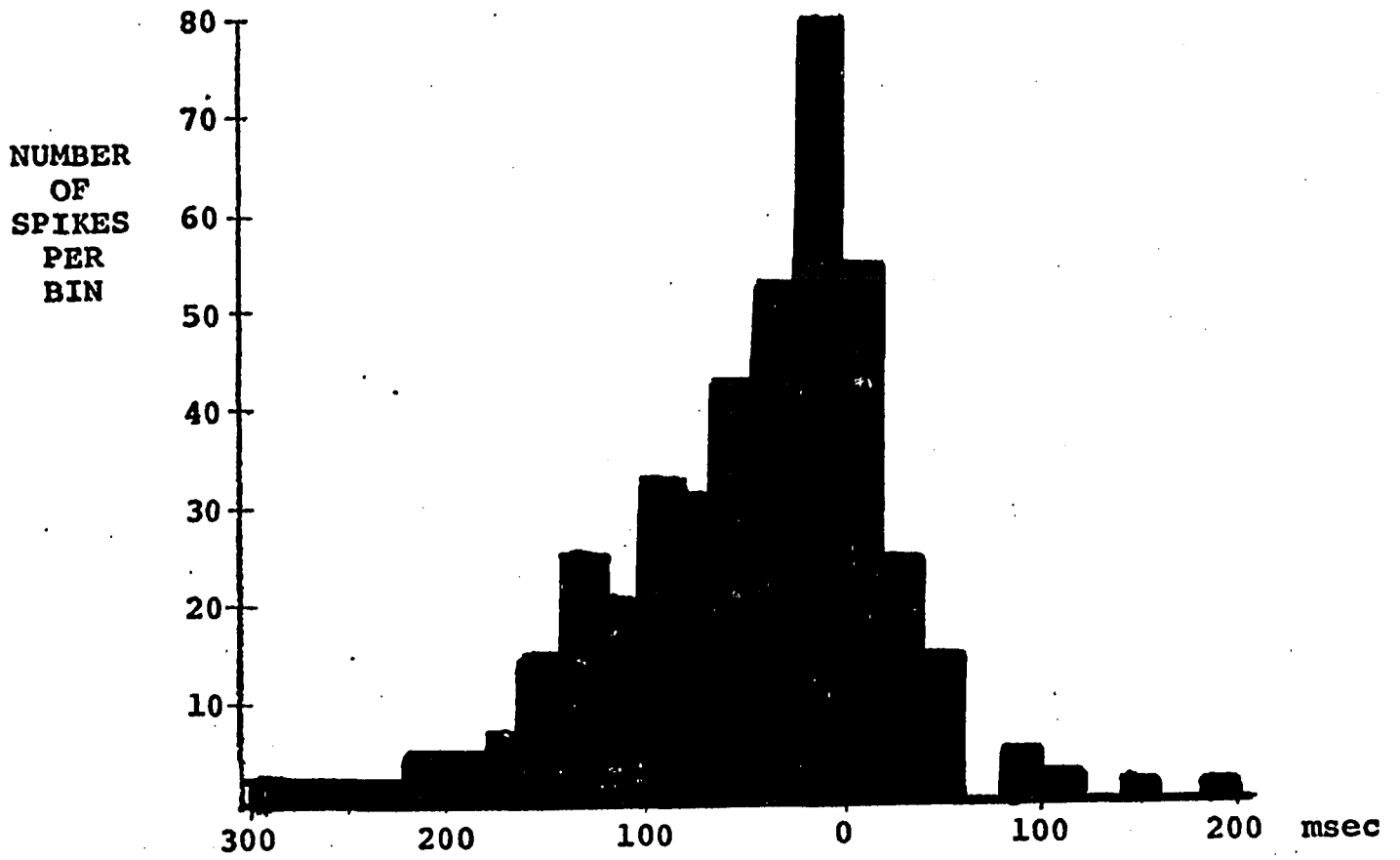
Does the Cortex Have a Role in Saccadic Eye Movement Initiation?

In contrast to the animal experiments, the gross potential data recorded from the human scalp during the performance of saccadic eye movements revealed phasic activity that clearly preceded the onset of eye movement by as much as 200 msec. The temporal characteristics are appropriate for a motor command to initiate the eye movement. Moreover, the morphology and temporal characteristics of the gross potentials that have been recorded from the human scalp are similar to the cumulative histograms of single unit responses recorded by Schiller and Koerner (1971) from the SC of the alert monkey (Figure 34). The unit illustrated began firing 200 msec prior to the onset of eye movement, increased firing until reaching a peak at 20-40 msec before saccade, after which it rapidly declined. The scalp recorded antecedent potentials in the present experiments showed a similar ramp-like activity beginning 60-190 msec before the saccade. Although it is not possible to know with certainty the underlying neuronal activity reflected as gross potentials at the surface, it is thought that this activity primarily represents the summing of post-synaptic potentials. The initial portion of the antecedent potentials recorded in these studies might well reflect the recruitment of eye movement related cells until a threshold is reached to trigger the neural activity initiating the saccade. The sharp phasic potentials have the

Figure 34: Top: Cumulative histogram of 30 saccade associated unit responses from the superior colliculus of the alert monkey. Bin width is 20 msec. Eye movement onset at 0.

(Taken from Schiller and Koerner, 1971)

Bottom: Potentials associated with 300 eye movements in the dark. Electrode placement: mid-parietal referred to linked ears. Eye movement onset at arrow. Time scale as for above.



appropriate timing to represent activity within the saccadic system which would activate the final common pathway leading to eye muscle activation.

If the antecedent activity represents a motor command signal to initiate an eye movement, why was there a similar distribution of potentials with maxima in the parieto-occipital and posterior frontal regions both during the performance of eye movements in the dark and under conditions of illumination? This observation does not fit the classical notion that the FEF mediates voluntary eye movements, for if it did, we should expect the FEF to display more prominent antecedent activity and the PEF activity to be reduced in the absence of visual input. There are, however, abundant cortico-cortical connections between the FEF and PEF. Reciprocal connections between the FEF in monkey and the area surrounding the intraparietal sulcus, particularly the inferior parietal lobule, have been traced (Pandya and Kuypers, 1969; Pandya and Vignolo, 1971; Kuypers, Szwarcbart, Mishkin, and Rosvold, 1965). It should be recalled at this point that stimulation of the inferior parietal lobule elicited eye movements (Fleming and Crosby, 1955). No projections were found, however, from the FEF to the peristriate belt, which has a considerable projection to the FEF. A modest projection from striate cortex to FEF was found. Thus, there are anatomical pathways linking the FEF and the PEF which would be capable of transmitting signals recipro-

cally. It is likely, therefore, that even if the presumptive command signal were generated within the FEF, that this activity would be readily propagated to the PEF, as well as to the SC and PPRF.

It is not possible to estimate the relative strength of the cortical generators based solely on amplitude measurements of scalp recorded potentials, since these reflect not only the size of active cortex and the magnitude of post-synaptic activity, but also the geometry and nature (i.e., excitatory vs. inhibitory) of changes in membrane polarization. Thus, a small active region can appear as a disproportionately small scalp potential (Vaughan, 1973). It can be inferred from the negative unit data that even if present, the FEF cells which encode each specific saccadic vector are relatively few in number and localized within a circumscribed cortical region. Thus, the rather unimpressive size of the frontal antecedent potentials is not entirely unexpected.

To summarize, data from the present and previous experiments implicate three areas in the initiation of saccadic eye movements -- the FEF, PEF, and SC. The potentials recorded in the present experiments overlying the cortical eye fields possess appropriate temporal characteristics to reflect motor command signals. Thus, the recording data obtained from Wurtz's and Schiller's studies of the SC together with the cortical data support the notion that all of these structures are in some way implicated in the initiation of saccadic eye movements. Although these

systems apparently are able to function independently to sustain saccadic eye movements, as may be concluded from the lack of permanent deficits following discrete lesions of these areas, it is likely that they function in a closely integrated manner in the intact organism.

Saccadic Eye Movements and Vision

The lack of movement of the visual field despite frequent shifts of gaze during normal viewing has led many workers to experimentally analyze the features of this "saccadic suppression." Small elevations of threshold for the perception of visual stimuli both prior to and after eye movements have been found (Volkman, 1962; Latour, 1962; Zuber and Stark, 1966; Duffy and Lombroso, 1968), but there has been no agreement as to whether central or retinal mechanisms were responsible for these observations.

In an electrophysiological study of saccadic suppression, Gross, et al. (1967) presented unpatterned stimuli at varying intervals after the onset of saccadic eye movements. The slight elevation in threshold to the test stimuli, as was found previously, was confirmed, and the accompanying evoked response was minimally reduced. The authors then more closely approximated the normal visual field by substituting a patterned field for both the background and the test stimulus. In these experiments, SS shifted their gaze over a patterned field, and at varying intervals after saccadic initiation, a complementary pattern

was substituted. Perception of the test stimulus in these experiments was suppressed and the accompanying evoked response was substantially reduced. It was, therefore, concluded that the presence of a patterned field was a necessary condition for suppression. These observations were later confirmed by Mitrani, Mateeff, and Yakimoff (1971).

MacKay (1970) reported suppression in the absence of eye movements when a small unpatterned field was moved across the retina. He found that a similar threshold elevation preceded and accompanied the stimulus movement as found associated with active movements.

In accounting for these observations, Vaughan (1970) explained that the suppression following saccades was a result of the strong burst of excitation evoked at the onset of eye movement (i.e., the lambda response) which would cause refractoriness to further stimulation. This refractory state would then suppress the response to visual input during and for a time following the saccade. Thus, we can account for the importance of a patterned field in generating strong suppression of input during saccades.

This mechanism, however, cannot account for the observation of apparent movement of the visual field with passive movement of the eyeball. Under these conditions, lambda-like responses have been recorded, triggered by the passive movement, which were temporally and morphologically similar to the lambda response evoked

actively by eye movements (Scott and Bickford, 1969). A refractory period is not sufficient to explain the subjective movement of the visual field with attempted movement of the eyes reported by patients with extraocular muscle paralysis. Under these conditions, it is feasible to invoke the concept of a corollary discharge which would be responsible for integrating the intended movement with the resulting visual input. This would permit visual stability under normal viewing (and visual instability with aborted or passive movement).

This notion (originally due to Helmholtz [1867]) was supported by Sperry (1950) who proposed a mechanism which would allow for compensation for a change in retinal displacement caused by a movement of the eyes, head, or body. A "corollary discharge" to the visual centers would signal a forthcoming change in retinal displacement allowing a specific adjustment to be made within the receptive areas prior to the movement, in order to maintain visual stability. Thus, the visual centers are kept in "constant adjustment" with respect to movement of the eyes, head, and body. Other variations on these ideas have been discussed by von Holst and Mittelstaedt (1957), Teuber (1966) and MacKay (1966).

Although the specific structures implicated in these processes are not known, there is clinical and experimental evidence to suggest that interaction of the visual and

motor processes associated with saccades occurs within both the parieto-occipital and frontal regions.

Although prestriate cortex, including portions of the parietal lobe, was classically considered to be a "visual association area," controversy raged over the specific visual perceptive deficits caused by experimental lesions to this region (Lashley, 1948; Chow, 1951; Evarts, 1952; Ades, 1946; Ades and Raab, 1949). Recently, the work of Mishkin (1972) and Gross (1973) has clarified the role of the prestriate region in visual perception. These workers placed small lesions in the "foveal" prestriate cortex of the monkey, a region in the ventrolateral prestriate area. Since this region is largely buried in sulci, it has never been totally removed in previous studies. Lesions in this area produced severe pattern discrimination deficits, not seen with lesions in other areas, including infero-temporal cortex. It is clear, then, that prestriate cortex, in addition to mediating eye movements when electrically stimulated, plays an important role in pattern vision.

Based upon tests with brain injured veterans, Semmes Weinstein, Ghent, and Teuber (1963) distinguished between two systems concerned with visuo-spatial perception. Wounds limited to the posterior parietal region disrupted visuo-spatial relationships in the extra-personal sphere; that is, between objects in space. On the other hand,

the perception of relationships between the person and the object was deficient in patients with injury to the frontal lobe. These functional distinctions were experimentally confirmed by Pohl (reported by Mishkin, 1972) who lesioned these areas in monkeys and found that frontal ablations disrupted the discrimination ability of the monkey to distinguish between two identical stimuli based upon their relationship to him. Monkeys with parietal lesions (portions of prestriate cortex were also ablated) were deficient in the discrimination of two objects with reference to an external landmark. These tests were also dependent upon visual discrimination ability, which was thus selectively impaired depending upon the location of the lesion.

A sensory role for the frontal cortex (particularly the FEF) was hinted at by the early work of Bianchi (1895), Kennard (1939) and Welch and Stuteville (1958) among others, who found that monkeys with lesions of the FEF displayed a neglect of stimuli entering the visual field. The sensory component of this visuo-spatial neglect was elegantly demonstrated by Latto and Cowey (1971) who plotted the visual fields perimetrically and found an hemiambyopic deficit in monkeys with FEF lesions. In intact monkeys, Mohler, et al. (in press) have also demonstrated that units in the FEF display visual receptive fields.

Additional evidence supporting the parieto-occipital and posterior frontal regions as the site of visuomotor integration comes from electrophysiological studies in man. The distribution of the components of the visual evoked response (VER) implicates these cortical areas in visual functions. The first component of the VER, a positive wave appearing at a latency of approximately 100 msec after the onset of visual stimulation (designated as the P100 component of the VER) has an occipital source mainly area 17, extending somewhat into area 18 (Vaughan, 1969). This distribution of the P100 component is similar to that found for the comparable component of the VER to a shift of pattern in the present experiments. After the initial positive wave and a subsequent negative deflection, a second positive component (called the P200) appears. The distribution of this component is more widespread with a maximum in the posterior parietal region, including area 19. A second focus of activity appears in the posterior frontal region. (This was found only for subject WR in the pattern shift condition in the present experiments). Thus, both the posterior parietal and posterior frontal regions are implicated electrophysiologically in the processing of visual information.

The distribution of the antecedent potentials associated with saccadic eye movements matches quite well the distribution of the P200 component of the VER. Moreover,

the lambda response seems to be limited to the occipital region and does not appear in the parieto-occipital or posterior frontal regions. The lack of saccade-related responses in these regions could possibly be related to the absence of subjective discontinuity of vision during eye movements. Furthermore, it is possible that the antecedent activity represents neural mechanisms associated with the corollary discharge, since the distribution of this activity is the same as that of the later evoked potential components. Thus, the oculomotor command signal could be integrated with the visual input to these areas so as to preserve the stability of the field in the face of discontinuous input.

Computation of the Saccadic Vector

An associated aspect of the visuomotor mechanisms during normal viewing is the programming of the direction and amplitude of saccades, utilizing the information obtained from the previous fixation in coordination with the goals of the viewing. What determines the target of the next saccade? Although the present experiments were not designed to test hypotheses concerning this question, it is important to note that the antecedent activity could in part reflect the processing of data to define the vector of the next eye movement. The cortical areas of maximal antecedent activity would be logical sites for this computation, since they are implicated in visual information processing as well as

eye movement control. Moreover, the temporal characteristics of the potentials are consistent with this task. As tempting as this notion might be, further experiments are needed before arriving at any firm conclusions concerning this mechanism.

Thus, it is possible that the antecedent activity associated with saccadic eye movements could reflect (1) neural activity underlying the motor command signal to move the eyes; (2) the corollary discharge maintaining the subjective visual stability of the field during saccades; and (3) the mechanism which computes the target of the subsequent saccadic eye movement. These functions are not necessarily mutually exclusive and further experiments are required to more precisely define the role of the cortex in these mechanisms.

Among the unresolved issues is the contradictory results of FEF recording and stimulation in monkeys. These conflicting observations must be clarified before an unequivocal role of the FEF in the initiation of eye movements is tenable. A possible approach to the problem would be to stimulate and record from the same site within the FEF as Schiller has done in the SC. Robinson and Fuchs elicited saccades of a specific amplitude and direction by stimulating specific sites within the FEF. It would be advantageous to record from these same sites while the monkey is performing the prescribed saccade as was defined by the stimulation

results. In addition, gross potential recordings should supplement the unit recordings, so as to evaluate possible error due to microelectrode sampling bias. The same studies need to be done in the PEF to define the potential role of this complex region in oculomotor control.

Once these data are obtained, simultaneous recordings in chronically implanted monkeys from the FEF, PEF and SC during the performance of saccadic eye movements would permit a comparison of the neural activity associated with eye movements in all three of the structures implicated in eye movement initiation. The relative strength of one center over the others could be assessed, as well as temporal differences in the activity recorded from each structure.

Future experiments will also have to deal with the question of what defines the target of the next saccade. These experiments can be carried out in human subjects utilizing psychophysical as well as electrophysiological techniques to determine how stimuli and goal interact to define the next saccadic vector.

To sum up the findings of the present study, brain potentials have been recorded both preceding and following voluntary saccadic eye movements. The scalp distribution of the antecedent potentials revealed two areas of maximal activity -- the parieto-

occipital and the posterior frontal regions, which overlie the classical cortical eye fields as defined through stimulation studies. The functional significance of these potentials, based upon their scalp distribution and time course, was discussed. The possibilities that the antecedent potentials might reflect in part the neural activity concerned with the motor command, the corollary discharge, and preparation for the subsequent saccade were considered. The theoretical and empirical basis for these proposals was discussed.

The lambda response, which followed eye movements over a patterned field, was revealed to have a distribution limited to the occipital region. The VER to shifts of the same pattern disclosed not only similar morphological and temporal characteristics, but a comparable scalp distribution as well. Both responses were altered by a reduction in field luminance by increased latency and decreased amplitude. Based upon these findings, which confirm observations by others, the lambda response was thought to be an evoked response due to the change in retinal stimulation at the onset of the saccade.

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