THE MAMMALIAN MIDBRAIN AND ISTHMUS REGIONS

PART II. THE FIBER CONNECTIONS

D. THE PATTERN FOR EYE MOVEMENTS ON THE FRONTAL EYE FIELD
AND THE DISCHARGE OF SPECIFIC PORTIONS OF THIS FIELD
TO AND THROUGH MIDBRAIN LEVELS

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SIX FIGURES

For several years the nuclear groups (Huber et al., '43) and the fiber connections (Woodburne, Crosby and McCotter, '46; Crosby and Henderson, '48; Crosby and Woodburne, '51) of the midbrain have been of interest to some of the members of the neuroanatomy group at Michigan. It has been found that certain fiber bundles can be followed more easily in either normal or degenerated material from their origins outside of the midbrain to, or through, this area than by direct midbrain lesions, particularly if paths in the midbrain tegmentum are under consideration. Among the important constituents of this tegmental area are cortico-bulbar bundles passing to the oculomotor or trochlear nuclei or, through the midbrain, to the abducens nuclei from the portions of the frontal cortex concerned with ocular deviation. The present study is concerned with such cortico-bulbar systems and with the specific patterns of eye deviation characterizing the frontal eye fields from which these systems arise.

Using sterile technique and ether anesthesia, the greater part of the frontal eye field was exposed 15 times (in 11 monkeys). Of these, 8 were primary unilateral exposures of the

area and three followed an earlier operation in which the contralateral frontal eye field had been stimulated and at least partly destroyed. In one monkey this eye field was exposed in each hemisphere and then bilateral stimulation was carried out. Twice the exposure of the frontal eye field was incidental to that of area 4 and the field was either destroyed or its stimulation was of a minor character. Except for those cases in which the selective destruction of areas 18 and 19 (Henderson and Crosby, '52) preceded the stimulation of the frontal eye field, there was a surprising agreement in the results. Many of the animals used in this work on the frontal lobe were also studied for optokinetic nystagmus before and after the removal of areas 18 and 19. The results of this study are reported in a paper by Henderson and Crosby ('52) which contains the protocols for all the monkeys tested for such nystagmus.

The brains of the monkeys in which lesions had been made in the frontal eye fields were prepared for study by the Marchi technique of Swank and Davenport ('35). These monkeys had been allowed to survive three weeks after the stimulation and the immediately following destruction of the fields or, where there had been bilateral lesions, three weeks from the time of the first operation.

The monkeys used in these experiments were partly male (3) and the rest female. They ranged in weight from $4\frac{1}{2}$ to 9 pounds and their estimated ages were between two and 4 years.

The animal must be on the verge of consciousness to obtain upward eye movements from stimulation of the appropriate portion of this frontal cortex. Downward movements, also, may be obtained only when the anesthesia is very light but horizontal deviations appear when the animal is somewhat more deeply anesthetized although still under a light anesthesia. Because of this need for accurate, rapid control of the anesthesia, ether was used in the present experiments. Possibly other anesthetic agents, properly handled, would yield like results.

For most of this series a Phipps and Bird Inductorium was used, set as for the stimulation of motor cortex (with a reading at 2 to 2.5). When a Model 3C Grass Stimulator became available the pattern on the frontal eye fields was rechecked (see monkey M-37, table 1). Using a monophasic wave the readings for the Grass Instrument were: frequency 30 to 50 per second, voltage 5 to 7, pulse duration 1 millisecond. A unipolar electrode was employed for stimulation with the indifferent electrode in the rectum. The lesions were made with a National electro-cautery. Stimulation of this area with a bipolar electrode is being done in connection with other experiments.

LITERATURE

In 1874, Ferrier reported horizontal eye movements in the monkey from the stimulation of the middle frontal gyrus in the region rostral to the "arm" area of the motor cortex. He also obtained a dilatation of the pupils from this portion of the cortex.

Ten years later, Ferrier and Yeo (1884), working with monkeys (macaque and dog-faced monkey), found that after unilateral ablation of the frontal eye field the head and the eyes deviated toward the side of the lesion, but that such deviation had disappeared by the 9th day. Following bilateral lesions in this brain area, the ability to turn the head and the eyes toward either side was impaired.

In 1888, Horsley and Schäfer stimulated the middle of the frontal lobe, in front of the motor cortex, in various kinds of

monkeys. They obtained conjugate deviation of the eyes in the horizontal plane toward the side opposite stimulation together with associated head movements. Closing of the lids followed stimulation of the motor "face" area.

In the same year, Beevor and Horsley, using Macacus sinicus, obtained a simultaneous turning of the head and the eyes away from the side of stimulation from an extensive region of the frontal cortex rostral to the motor area. In addition, excitation of the upper portion of the frontal eye field, and adjoining regions, produced a deviation of the eyes upward and toward the other side. Stimulation of the lower part of this field resulted, once, in a downward deviation. Rarely, dilatation of the pupils accompanied the turning of the head and the eyes. Convergence occurred when the middle of the lower half of the frontal eye field was tested. In 1890, these observers, using again Macacus sinicus, reported a raising of the lids on stimulation of the frontal eye field and documented some of their earlier findings. At this time they pointed out that the discharge path from this field lies in front of the motor path from the "face" area in the internal capsule.

Using several kinds of monkeys (as the bonnet monkey and the macaque), Mott and Schaefer (1890) stimulated the frontal eye region. They obtained conjugate horizontal deviation of the eyes from the upper portion of the area, obliquely upward and lateral deviation from its lower portion, and a downward and lateral turning of the eyes from the part of the frontal lobe which is now usually allocated to area 6. Bilateral stimulation of the appropriate areas produced straight upward and downward eye movements. They noted that these were more discrete in the larger monkeys. An appropriate turning of the head was associated with the deviation of the eyes in various directions. When the portions of the frontal cortex and the occipital cortex (areas 18 or 19) were simultaneously stimulated, but in opposite hemispheres, the dominance of the frontal area over the occipital area became evident. The data from the much later neuronography studies of McCulloch ('49) and the experimental work of Henderson and

Crosby ('52) are in accord with these early studies by Mott and Schaefer.

In the cat and in two types of monkey (Macacus rhesus and Macacus sinicus), Sherrington (1893) demonstrated that excitation of the region of the brain rostral to the motor cortex produced conjugate horizontal deviation of the eyes toward the other side. After cutting the left oculomotor and left trochlear nerves this observer, on stimulation of the appropriate part of the left eye field, still obtained horizontal deviation of the eyes to the right (see also Bender and Fulton, '38). This experiment was followed by others of like intent. Sherrington pointed out that the frontal cortex may exert an inhibitory as well as an excitatory effect over the turning of the eyes in various directions.

Risien Russell studied eye movement following cortical stimulation in dogs and cats (1895) and in the macaque (Macacus sinicus, 1894). In each case he cut the muscles producing horizontal deviation of the eyes to one side and then demonstrated, on stimulation of the opposite frontal cortex, either an upward turning of the eyes or a downward deviation, the direction of movement depending upon the specific portion of the area involved. He claimed that horizontal movements, being much more readily obtained, tended to mask upward and downward movements. By this method he laid out a pattern for eye deviations on the frontal cortex of the monkey somewhat comparable to that described in the present report (see figs. 1 and 2 and p. 367). Thus he obtained: upward turning of the eyes from the region corresponding to the dorsal subfield of the present account (but only from near the apex) and from area 6; downward eye movements from the lower part of the frontal eye field near the apex and from the frontal part of area 4; and convergence from the anterior part of the apex (near the caudal tip of the sulcus principalis, or the sulcus frontalis of Smith, '49).

In higher apes (gorilla, orang-utan, and chimpanzee) Grünbaum and Sherrington ('01) demonstrated that the area of the frontal cortex rostral to the motor area, and wholly separated

from it, is concerned with conjugate deviation of the eyes in the horizontal plane.

Jolly and Simpson ('07) obtained horizontal eye movements. to the usual side and an opening of the eyes with associated head movements from the area which corresponds to the dorsal subfield of the present account (fig. 1). From the motor area behind the apex (fig. 1) they demonstrated a closing of the eyes.

Vogt and Vogt ('07) described eye movements from the frontal lobe in a series of lower primates (Cercopithecinae) including the macaque. They obtained horizontal eye movements 16 times, deviation up and toward the other side 8 times, and down toward the other side once. These movements were often, but not invariably, accompanied by pupillary changes and, in those with an upward and downward slant, by appropriate lid movements. They were obtained from an area which extended from the arcuate fissure forward, above and below the frontal fissure, to a plane slightly in front of its caudal tip. In 1919 the Vogts reported horizontal deviation of the eyes (in Cercopithecinae) from fields 8 β (where the eyes also had an upward slant), 8 α and 8 δ, from parts of area 9, and from area 10. The strength of stimulus necessary to elicit the deviations varied from field to field and the turning of the eyes was often in association with various adversive movements.

Levinsohn ('09) obtained deviation of the eyes toward the other side and down from the frontal eye fields above the frontal fissure and apparently from part of area 6. Stimulation of the rostrodorsal part of area 6 gave opening of the lids and horizontal deviation of the eyes. From one point immediately ventral to the caudal tip of the frontal fissure he obtained a deviation of the eyes upward toward the other side. This pattern differs from that described by the Vogts and by others.

In 1917, Leyton and Sherrington, working with higher primates (chimpanzee, orang-utan, and gorilla), elicited a horizontal conjugate deviation of the eyes toward the side opposite stimulation from the first and second frontal gyri. This move-

ment was modified, in some cases, by a slightly upward or downward tilt. Occasionally they obtained convergence. These observers pointed out that, in the young gorilla, the frontal eye field is divisible into an upper and a lower subfield by a horizontally running, inexcitable field. The animal's eyes opened before eyeball movement occurred when the lower subfield was stimulated. Stimulation of the upper subfield resulted in a simultaneous opening and deviation of the eyes or, in some cases, a turning of the eyes preceded by a raising of the lids. One of the most significant parts of this paper by Leyton and Sherrington is their report that a raising of the lids, sometimes associated with a deviation of the eyes, can be obtained from stimulation of the precentral area. It is interesting that they regarded such eye and lid movements as secondary to movements of other parts of the body.

As a part of his well known English lecture on the functions of the cerebral cortex, Foerster ('31) discussed briefly the results of stimulation of the posterior part of the second (or middle) frontal convolution in man. Previously he had obtained a conjugate horizontal deviation of the eyes, and, occasionally, an obliquely upward deviation of them to the side contralateral to stimulation. He pointed out that ablation of this portion of the middle frontal gyrus may result in a temporary paralysis of such horizontal deviation toward the side opposite the lesion.

Mettler ('35) reported, following the ablation of portions of the frontal cortex of the macaque (Macaca mulatta) including a part of the frontal eye field, the presence of degenerated fibers to the motor nuclei of the nerves supplying the eye muscles. He stated that he could trace Marchi granules to the oculomotor nucleus and to pontal nuclei. He does not state specifically that he followed degenerated fibers to the abducens nuclei.

On excitation of the frontal eye fields of the cat, Spiegel and Scala ('36) produced a conjugate deviation of the eyes in the horizontal plane toward the side opposite stimulation. Other points in this field yielded convergence or divergence of the

eyes. They considered that vestibular centers must be intact in order that horizontal eye movements may occur.

In 1936, Levin carried out a series of experiments on the frontal lobes of macaques. This series included ablations which involved portions of the frontal eye fields. Following a lesion which destroyed the apex of the frontal eye field (as the term is used in the present account, A, fig. 1, p. 368) he traced degenerated fibers through the anterior limb of the internal capsule and the medial portion of the cerebral peduncle into the substantia nigra and the tegmentum of the midbrain.

Using stimulation methods, Smith studied certain frontal lobe regions in the cat ('40) and the macaque ('36, '40, and '49). In the cat, he obtained head and eye movements in the horizontal plane and pupillary dilatation from portions of this lobe medial to the rostral wall of the cruciate fissure. In the monkey ('49, fig. 107, p. 313), he elicited eye or lid movements from an area extending from the superior sagittal fissure through the upper half and then the caudal one-third of the lower half of the frontal eye field and into the precentral gyrus. Stimulation of this portion continuing into the precentral area produced a closure of the lids; the frontal eye field gave successively, from above downward: (1) pupillary dilatation; (2) an "awakening response"; (3) horizontal conjugate deviation of the eyes toward the side opposite stimulation; and (4) a nystagmus to the opposite side. This 1949 paper by Smith provides a very good review of the pertinent literature up to the date of its publication.

The work of Penfield and his associates (Penfield and Boldrey, '37; Penfield and Erickson, '41; Rasmussen and Penfield, '48; Penfield and Rasmussen, '50) has particular interest because it is based on observations in the operating room. A considerable portion of the operative work on these patients was done under local anesthesia. Various regions of the brain were explored; among them were some areas which were related to eye movements.

Penfield and Boldrey ('37) reported horizontal deviation of the eyes toward the side opposite stimulation (a so-called ad-

versive movement) particularly from the frontal eye field but also from the precentral gyrus. Likewise, they obtained, from the caudal part of the mid-lateral area and the lower adjoining region of this frontal field and from certain portions of area 4, deviation of the eyes upward and toward the contralateral side.

In the case reports in their book on epilepsy, Penfield and Erickson ('41) described abnormal eye positions or deviations during epileptic attacks. These occurred where the epileptic foci included, or bordered upon, brain areas functionally related to eye movements.

The contributions by Rasmussen and Penfield ('48) and Penfield and Rasmussen ('50) contain valuable accounts and charts showing the points on the brain which yield deviation of the eyes on stimulation. From both the frontal eye field and the precentral region (area 4) they were able to elicit a turning of the eyes in various planes. Those interested in the exact location of these various points should consult the original text (see Penfield and Rasmussen, '50; figs. 30 to 34, pp. 68 to 73). In general these observers found that two-thirds of such deviations of the eyes were obtained from the area in front of the motor cortex and two-thirds of the lid movements from the region close to the central fissure. Such eyelid movements occurred independently, in connection with other face movements, or in association with deviation of the eyes. The results of Penfield and Rasmussen indicated that the stimulation of the frontal eye field usually produces adversive eye movements but that stimulation of appropriate portions of the precentral gyrus may result in a turning of the eyes toward or away from the side of the stimulation and often in association with face movement.

Many research workers, dealing primarily with other problems, have reported horizontal deviation of the eyes (with or without an upward or downward slant) from stimulation of the frontal lobe rostral to the motor cortex. Such eye movements were often accompanied by other head or body movements. The clinical literature (for example the papers of

Penfield and his collaborators) contains numerous accounts of patients with frontal lobe involvements in which deviation of the eyes to one side was a prominent clinical sign. Many ophthalmologists (as Best, '41) dealing with occipital lobe lesions, or multiple lesions in the brain, have considered the possible interrelations of the frontal with the preoccipital and occipital eye fields. Practically all of these contributions give some attention to publications which their writers considered important for the matters under consideration, so that those interested in the literature on cortical fields related to eye movements can easily accumulate a large bibliography.

To attempt to review all of the literature is far beyond the intent and unrelated to the purposes of the present paper which is a simple preliminary report on eye deviations in monkeys as obtained under certain set experimental conditions. The papers selected, out of a large reading list, for consideration here are those which seemed to the authors particularly pertinent or, in some cases, those which had been less frequently mentioned. Certain types of papers have been omitted. Among these are publications dealing primarily with the preoccipital and (or) occipital eye fields, since such literature has been reviewed recently, though not exhaustively, by the present writers (Crosby and Henderson, '48; Crosby, '50; Henderson and Crosby, '52). Likewise not discussed at this time are papers dealing with special functions of the frontal eye fields, such as its possible relations to the vestibular centers (Bárány, Vogt and Vogt, '23; Spiegel and Sommer, '44), or those presenting evidence for hemianopsia — probably pseudo-hemianopsia — following frontal lobe lesions, or the excellent studies on pupillary changes to which the present writers have nothing significant to contribute at this time.

EXPERIMENTAL RESULTS

The shape of the frontal eye field is indicated somewhat diagrammatically in figure 1 and this figure should be consulted in connection with the following account. Purely for purposes of convenience in description, this frontal field has been sub-

divided into secondary portions which pass over into each other without any distinct boundaries. The terms applied here to such secondary subdivisions, while admittedly rather cumbersome, have the advantage of being noncommittal. Before any final terminology can be adopted much more experimental work is needed to determine the intricate interrelations of such subdivisions with other portions of the cortex.

In this discussion the following terminology is applied to the demonstrated secondary functional subdivisions of each frontal eye field (fig. 1) beginning near the sagittal fissure and proceeding downward over the lateral surface of the frontal lobe toward the lateral fissure: the dorsal extension of the dorsal subfield (DE); the transitional area between the dorsal extension and the dorsal subfield (dorsal transitional area, DT); the dorsal subfield (DS); the apex (A); the ventral subfield (VS); the transitional area between the ventral subfield and the ventral extension of that subfield (ventral transitional area, VT); the ventral extension of the ventral subfield (VE). The frontal eye field is separated from the sulcus principalis or sulcus frontalis (Smith, '49) by an inexcitable zone on both sides of the fissure (see also Leyton and Sherrington, '17) except possibly at the apex.

Stimulation of the various portions of the frontal eye field yielded the following results:

A. No eye deviations were obtained in one small monkey (table 1, M-30).

B. From the dorsal extension of the dorsal subfield deviation of the eyes obliquely downward toward the side opposite stimulation was obtained in three monkeys (table 1, M-19, M-32, M-37). From this same general area (and more particularly from its lower part), such deviation was accompanied, at times, by a raising of the lids which suggests the "awakening response" described by Smith ('49).

C. Divergence was obtained from the dorsal transitional area of two previously unoperated monkeys (table 1, M-14, M-37) and bilaterally from this area in a monkey (table 1,
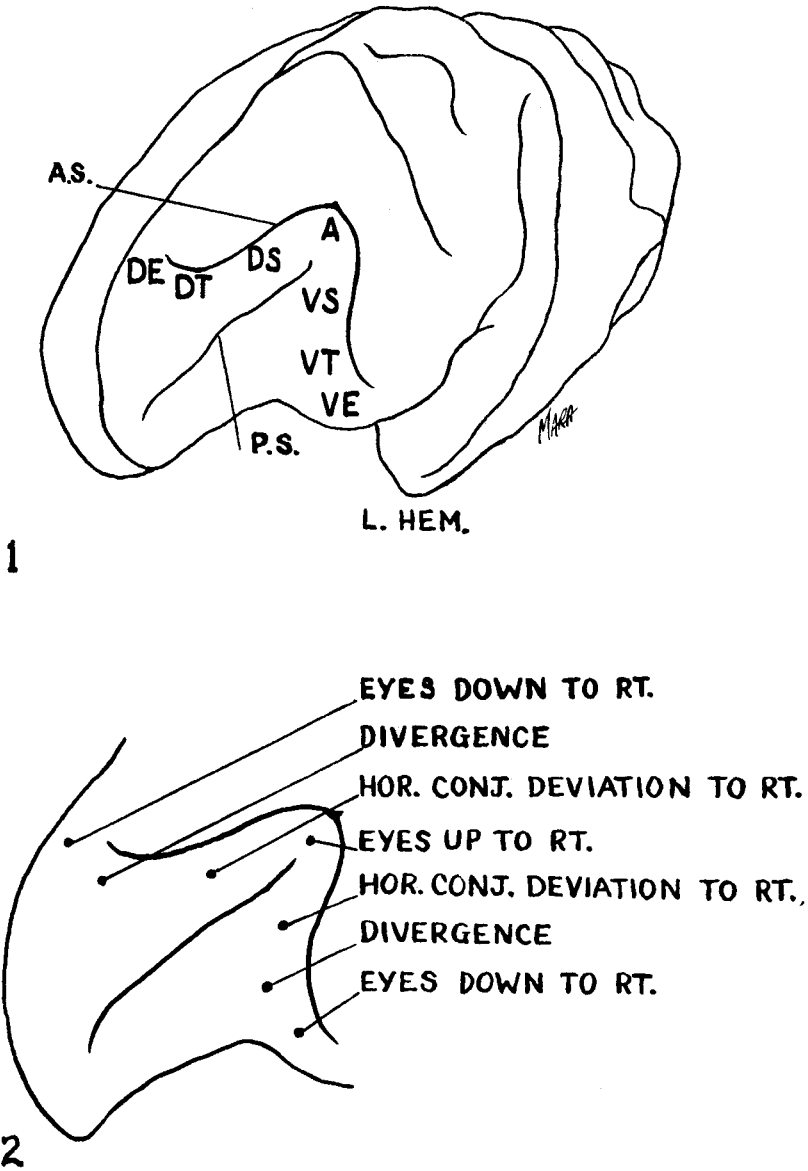
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Fig. 1   A drawing of the left hemisphere (L. HEM.) of Macaca mulatta, illustrating the position of the various subdivisions of the frontal eye field as described in the paper. A, apex; A.S., arcuate sulcus; DE, dorsal extension; DS, dorsal subfield; DT, dorsal transitional area; P.S., principal sulcus; VE, ventral extension; VS, ventral subfield; VT, ventral transitional area.

Fig. 2   A drawing of the left frontal eye field with the pattern of eye deviations projected upon it.

M-32) which had had an earlier removal of areas 18 and 19 on one side.

D. From the dorsal subfield, horizontal conjugate deviation of the eyes toward the side opposite stimulation was elicited in 7 monkeys (table 1, M-11, M-14, M-19, M-22, M-32, M-33, M-37), 4 of which were tested bilaterally.

E. In 8 monkeys (table 1, M-11, M-14, M-19, M-22, M-24, M-32, M-33, M-37), in 4 of which stimulation of the apex was carried out on both sides of the brain (but at different times), an obliquely upward turning of the eyes toward the side opposite the excitation was obtained.

F. The ventral, like the dorsal subfield, yielded a horizontal conjugate deviation of the eyes toward the side opposite stimulation. This was demonstrated in 7 monkeys (table 1, M-11, M-14, M-19, M-22, M-32, M-33, M-37), three of which were tested on each side.

G. Divergence was obtained from the ventral transitional area of 4 monkeys (table 1, M-11, M-14, M-32L, M-37) which had not been operated upon previously, of one monkey (M-22) in which both right and left ventral transitional areas were exposed and stimulated independently, and from still another monkey (M-32R) from which areas 18 and 19 had been removed on one side.

H. In two monkeys (table 1, M-22, M-33) a turning of both eyes obliquely downward away from the side stimulated was obtained from the ventral extension of the ventral subfield. In one monkey (M-32) in which the left areas 18 and 19 and the ventral subfield of the left frontal eye field had been destroyed, the obliquely downward deviation of the eyes obtained from the remaining right ventral extension was directed toward the side of stimulation.

In a single operation on one monkey (table 1, M-22), a bilateral exposure of the frontal eye fields (except for their more dorsal portions) was made. After testing the deviations of the eyes in various planes from the appropriate portions of each field, simultaneous bilateral stimulation by use of two electrodes from the same stimulator was carried out. When

TABLE 1[1]

MONKEY	DATE OF EXPERIMENT	SIDE	PREVIOUS OPERATION	HORIZONTAL EYE MOVEMENT		UPWARD EYE MOVEMENT	DOWNWARD EYE MOVEMENT		DIVERGENCE		COMMENTS
				DS	VS	APEX	DE	VE	DT	VT	
M-11	10/6/49	Right	None	+	+	+				+	
M-14	1/31/50	Left	None	+	+	+			+	+	
M-14	2/9/50	Right	Left frontal eye 1/31/50	+	+	+			+		
M-18	7/12/50	Left	Left area 19 7/5/50	Ablation of a portion of the left frontal eye field no stimulation							
M-19	9/3/50	Right	None	+	+	+					
M-19	9/7/50	Left	Right frontal eye 9/3/50	+	+	+	+				
M-22	10/4/50	Right	None	+	+	+		+		+	
M-22	10/4/50	Left	None	+		+		+		+	
M-24	11/10/50	Right	None			+ (only apex exposed)					Area 4 stimulated for eye movements
M-29	11/16/50	Right	None	Frontal eye field not stimulated							Area 4 stimulated for eye movements
M-30	1/15/51	Left	None	+	Stimulated, but no movements obtained						
M-32	2/15/51	Left	Left areas 18 and 19 2/8/51	+	+	+	+		+	+	
M-32	3/1/51	Right	Left frontal eye 2/15/51	+	+	+		+	+	+	
M-33	3/13/51	Left	None	+	+	+		+	+	+	
M-37	5/4/51	Left	None	+	+	+	+		+	+	

[1] Various parts of frontal eye field (figs. 1 and 2): DE, dorsal extension; DS, dorsal subfield; DT, dorsal transitional area; VE, ventral extension; VS, ventral subfield; VT, ventral transitional area.

both apices were stimulated the eyes turned directly upward, when both dorsal or both ventral subfields were activated the eyes looked straight ahead. If the stimuli were applied alternately to each of the apices, as first to the right and then to the left, the animal turned its eyes obliquely upward toward the left and then obliquely upward toward the right. Upon alternate stimulation of both dorsal or both ventral subfields, the animal looked first to one side and then to the other, the eyes being directed away from the side of stimulation.

Ether anesthesia produces alterations in the size of the pupils making it somewhat difficult to obtain incontrovertible evidence of increase or decrease in pupillary size due to stimulation of the frontal eye fields. Moreover, the writers were concerned particularly with ocular deviations and their records on pupillary changes are incomplete. Unquestioned dilatation of the pupils due to the electrical excitation was obtained at least once from the dorsal extension of the dorsal subfield, the region allocated by Smith ('49) to this function.

Leyton and Sherrington ('17) and Penfield and his associates (Penfield and Boldrey, '37; Rasmussen and Penfield, '48; Penfield and Rasmussen, '50), as has been noted before, have reported a turning of the eyes in different directions as a result of stimulation of various portions of the primate area 4, particularly those portions in man bordering on the central fissure (Penfield and Rasmussen, '50). Motivated by these accounts, the present observers stimulated the "arm" and the "face" regions of area 4 in two monkeys (table 1, M-24, M-29), in one of which deviation of the eyes in various planes was elicited from along the central fissure (see fig. 1). Such deviations accompanied movements of the face or the arm, the type of movement depending upon the exact portion of the motor cortex stimulated. Leyton and Sherrington ('17) had regarded deviations of the eyes set up from the motor area of apes as secondary to a turning of the neck and the head. It seems quite possible that these eye movements obtainable from area 4 are a type of cortical associated movement. In any case they were less marked and often not conjugate in the monkeys studied for

the present report. Moreover, they were still elicitable in various planes after destruction of considerable portions (the dorsal subfield, the ventral subfield, the apex) of the frontal eye field, suggesting an independent path to the motor nuclei of the eye muscle nerves.

Evidences for pathways from the frontal eye field

A lesion was placed in the ventral subfield of the frontal eye area invading the lower part of the apex. The cauterization involved some other underlying fibers of the frontal lobe. Consequently, the degenerated fascicles in the internal capsule are greater in amount than those arising from the destroyed portion of the ventral subfield. The course of the degenerated abducens component of the cortico-bulbar system (see also Crosby, '50), as revealed by the Marchi preparations, is diagrammed in figures 3 and 4. Figures 5 and 6 are photomicrographs of such Marchi preparations illustrating critical levels in the course of this cortico-bulbar path related to the abducens complex. The degeneration can be traced from the internal capsule into the cerebral peduncle where Marchi granules lie in its medial half. Because of the bundles accompanying these degenerated cortico-bulbar fascicles it is not possible to be more explicit with regard to their exact position in this region. Beginning at mid-oculomotor levels (fig. 3), and at many intervals between these levels and the plane of abducens nucleus, fascicles leave the main pyramidal tract to join, and to proceed

Fig. 3   A diagram of the relation of the abducens component of the cortico-bulbar tract (CORT.-BULB. TR'.) from the ventral subfield of the frontal eye field to the contralateral abducens nucleus (NUC. VI). The course of the aberrant fibers within the medial lemniscus (L.) is illustrated.

Fig. 4   Diagrammatic representation of a transverse section through the pons showing the decussation of the abducens component of the cortico-bulbar tract (CORT.-BULB. TR'.), its position in relation to the abducens nucleus and the facial root, and its termination in the nucleus.

Abbreviations: CEREB., cerebellum; CORT.-BULB. TR., cortico-bulbar tract; CORT.-BULB. TR'., abducens component of cortico-bulbar tract; CORT.-PONT. TR., cortico-pontine tract; CORT.-SP. TR., cortico-spinal tract; L., medial lemniscus; LES., lesion; MED. LEM., medial lemniscus; M.L.F., medial longitudinal fasciculus; N.III, oculomotor nerve; N.VI, abducens nerve; N.VII, facial nerve; NUC.III, oculomotor nucleus; NUC.VI, abducens nucleus; NUC.VII, facial nucleus; P., parabducens nucleus; S.C., superior colliculus; SP.R.V., spinal root of the trigeminal nerve.
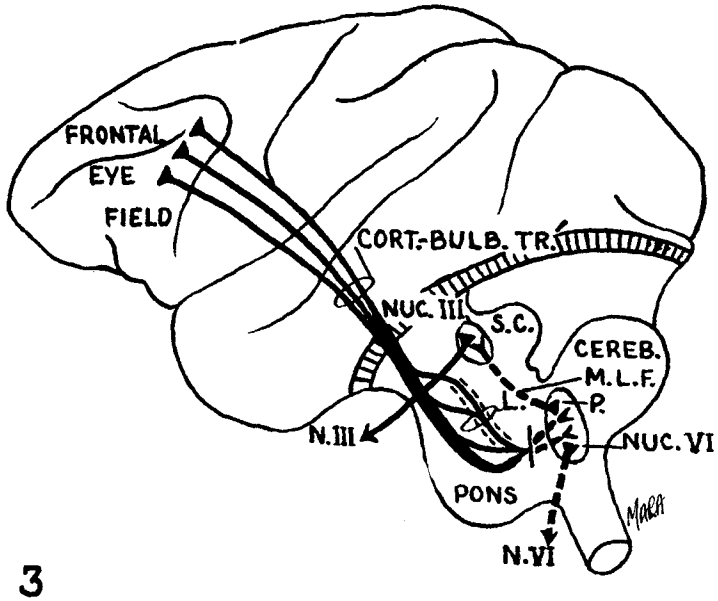
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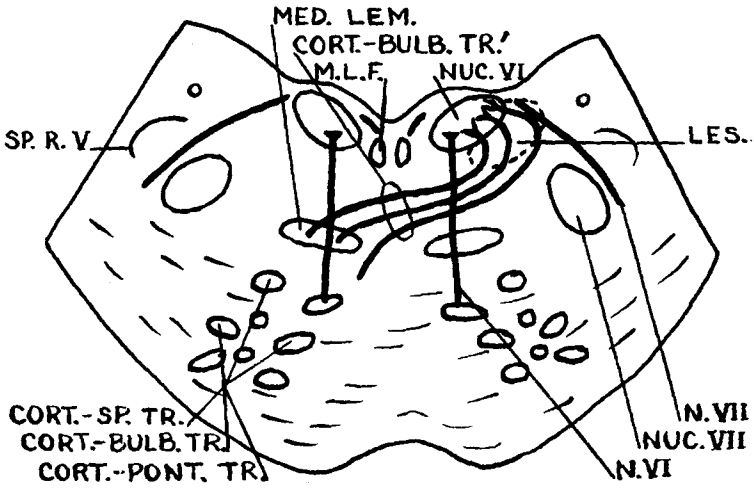
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Figures 3 and 4

caudad in (fig. 5), the medial lemniscus. Such bundles, presumably comparable to a portion of Dejerine's ('14) aberrant pyramidal system, extend to the lower third of the pons, then swing across the midline (figs. 4 and 6) and swing dorsolaterad to reach the lateral and ventrolateral side of the abducens nucleus, from which position degenerated fibers pass to this nucleus. These cortico-bulbar fibers, as they lie near the abducens nucleus, are in close relation to the facial root (fig. 4) where it arches around the lateral side of this nucleus in its course toward the ventral surface of the brain. A few scattered Marchi granules extending from the medial lemniscus toward the abducens nucleus suggest that some fibers of the cortico-bulbar system may end in the homolateral abducens nucleus. Also, this aberrant cortico-bulbar system is joined by coarser fascicles (figs. 4 and 6) which pass directly from the underlying pyramidal system to the contralateral abducens nucleus without coursing in the medial lemniscus.

As upper oculomotor levels are approached, in the plane where the first aberrant cortico-bulbar fibers for the abducens nucleus turn out of the peduncle to enter the medial lemniscus, a few degenerated fascicles extend more dorsomediad, to decussate obliquely in the upper third of the midbrain tegmentum and distribute to the anterior end of the oculomotor nucleus on the side to which they have crossed. They do not enter the farther caudal and more median portion of the nucleus where the cells of origin for the oculomotor fibers to the medial recti lie. They are regarded as cortico-bulbar fibers from the lower half of the apical region, which was included in the lesion. They are probably comparable to the fibers traced by Levin ('36) from this region of the frontal cortex into the midbrain tegmentum. Descending pathways from the frontal eye fields of primates to lower centers have been described more or less completely by various observers among whom may be mentioned Dejerine ('14), Hirasawa and Katô ('35), Mettler ('35), Levin ('36), and Crosby ('50). According to Smith ('49), as early as 1868 Prevost obtained deviation of the head and eyes along with hemiplegia from internal capsule lesions.

Some confirmatory evidence for the course of cortico-bulbar fibers from the frontal eye field to the contralateral abducens nucleus is offered by another less satisfactory Marchi series prepared following a lesion of the right dorsal subfield. The fascicles can be traced from this cortical area into the cerebral peduncle and more bundles than in the previous series sweep out of the peduncle into the medial lemniscus at upper oculo-motor levels. Such bundles are supplemented by additions from the pyramidal tract during the caudal course of these aberrant cortico-bulbar fascicles. No decussation of these cortico-bulbar fibers to the contralateral abducens nucleus is evident in this series. Behind the abducens level, the medial lemniscus does not contain Marchi granules.

The Marchi material has indicated that in the monkey the cortico-bulbar system as it turns into the abducens nucleus lies lateral and ventrolateral to that nucleus and, in part, in the course of the emerging motor facial root. That it occupies a similar position in man would appear to be indicated by the following case history.

A male patient, 58 years old, was admitted to Wayne County General Hospital in May, 1949. He reported the sudden onset, the week prior to admission, of a weakness of the right side of the face and an inability to look toward the right. These symptoms were accompanied by an attack of vertigo which lasted for an hour or so. Examination by one of us (Dr. Yoss) showed that the man had a complete facial paralysis of the flaccid type, indicating a facial root involvement on the right. He was unable to look voluntarily toward the right and could not follow a slowly, steadily moving finger toward that side. There was no strabismus and no other eye signs appeared. No additional motor loss and no sensory defects could be demonstrated. Two weeks after admission to the hospital there was a slight improvement of the facial paralysis but no change in the disability in eye movement. The case was diagnosed as a thrombosis of a small pontine vessel.

For purposes of the present discussion, the following facts with regard to this case are significant. (1) The right facial paralysis was of a lower motor neuron type, suggesting an involvement of the facial nucleus or the facial root. (2) There was an inability to turn the eyes voluntarily toward the side

of the facial paralysis suggesting that the appropriate regions of the contralateral frontal eye field or the abducens component of the cortico-bulbar tract was included in the lesion. (3) There was a loss of automatic following movements of the eyes toward the side of the facial paralysis, which indicated an involvement either of the contralateral parieto-occipital eye fields or, more probably, of their discharge path, the cortico-tegmental tract (Crosby and Henderson, '48), in its course to the abducens nucleus. The only region (fig. 4) in which the three systems — the facial root, the cortico-bulbar system and the cortico-tegmental tract — can be found in a common field and therefore be involved in a single lesion is the area lateral and slightly ventrolateral to the abducens nucleus, where the crossed cortico-bulbar (abducens component) and cortico-tegmental tracts lie close to the ventrolateral boundary of the abducens nucleus and the outgoing facial root swings along the lateral border of that nucleus interdigitating with some of the fascicles of the cortico-bulbar tract. This case provides an excellent illustration of the way in which additional anatomical data may afford a better neuroanatomical basis for clinical diagnosis.

DISCUSSION AND SUMMARY

The localization pattern within the frontal eye fields as demonstrated in the present paper does not agree exactly with that described by any other observers with whose work the present writers are familiar. It resembles most closely those patterns described by Leyton and Sherrington ('17) and Penfield and his associates ('37, '41, and, particularly, '48 and '50), which have already been discussed briefly in the review of the pertinent literature.

The most surprising feature of the localization pattern as here presented is its duplication, on each side of the cortex, in mirror-image fashion. Thus beginning with the apex of the left frontal eye field (figs. 1 and 2) and proceeding (above the sulcus principalis, or the sulcus frontalis of Smith ['49], and its bordering inexcitable area) through the dorsal subfield, the

dorsal transitional area, and then the dorsal extension of the dorsal subfield to the region of the superior sagittal fissure the following series of eye movements are obtained, in order, on appropriate stimulation: turning of the eyes upward and to the right; conjugate horizontal deviation to the right; divergence of both eyes; and, finally, deviation of the eyes downward and to the right. Testing of the direction and type of eye movements beginning with the apical region but continuing downward below the sulcus frontalis (and bordering inexcitable area) through the ventral subfield and then through the ventral transitional area into the ventral extension of the ventral subfield in the region near the lateral fissure reveals that the same orderly arrangement of eye movements listed for the dorsal half of the frontal eye field occurs in the localization pattern on the ventral half of the field but in a mirror-image fashion. Like results, but with the eyes directed toward the left, are obtained from the right hemisphere. It is to be stressed that a direct forward gaze or a deviation of both eyes straight upward or straight downward indicates a simultaneous and equal activity of the appropriate and like regions of both frontal eye fields.

In 1893, Sherrington suggested that the frontal eye fields may have both inhibitory and excitatory effects over the deviation of the eyes in various planes, his experimental work indicating that such effects may be exerted at lower motor neuron levels. There is considerable evidence that the frontal eye fields are dominant over those of the parieto-occipital regions of the brain and that this dominance may result in a suppression of the activity of the latter areas when the frontal regions of the cortex are directing eye movement. Dusser de Barenne, Garol, and McCulloch ('41) found that the electrical activity of the precentral gyrus was suppressed and the region rendered, for the time being, unresponsive to stimulation following excitation of the frontal cortex, including the frontal eye field, by electrical stimulation or by use of strychnine. Their results were in line with some experimental data reported by the Vogts ('19) on lower primates. These latter observers

noted that, with certain strengths of stimuli, not only were eye deviations elicited from the portions of their frontal eye field but the movements normally elicitable on stimulation of certain portions of the precentral gyrus were suppressed. Thus they failed to obtain facial movements on excitation of the proper part of the precentral gyrus when area 8 was stimulated by a not too strong current, or arm and finger movement from the motor area when area 8 was activated by a very weak current. McCulloch ('47, '49) obtained suppression of area 8 when area 19 was strychninized and suppression of area 19 and firing of area 18 when area 8 was activated with strychnine.

Henderson and Crosby ('52) have already considered that the frontal eye fields may, on occasion, inhibit, or at least suppress, the activity of the contralateral areas 18 and 19 and facilitate that of the homolateral fields. There is some evidence that the duplication of the localization pattern in each frontal eye field may be related to this dual activity (suppression and facilitation) but no conclusions can be drawn until further studies have been made.

Patients with irritative lesions in certain portions of the frontal lobe may lie with the eyes constantly directed toward one side. This is usually regarded by clinicians as an indication that the contralateral frontal eye field is involved in the lesion, producing a condition comparable to that set up in the monkey by unilateral stimulation of the dorsal and ventral subfields of this area. It seems quite probable that in patients (as in monkeys) gaze may be directed in other than horizontal planes providing the appropriate portions of the frontal eye field are irritated and that divergence (or bilateral external strabismus) of sudden onset and varying persistence, associated with other frontal lobe signs, may well indicate a cortical level only for the lesion.

Destructive lesions of the portions of the frontal eye field related to conjugate horizontal deviations of the eyes produce a turning of the eyes toward the side of the lesion and a paralysis of gaze to the other side in animals and man according to Levinsohn ('09), Bárány, Vogt, and Vogt ('23), Grinker and

Bucy ('49), DeJong ('50), and others. Foerster ('31) noted no deviation of the eyes toward the side of the injured frontal eye field in man. Paralysis of gaze to the opposite side was temporary. Such deviation as may occur is relatively transient (Spiegel and Sommer, '44) persisting, at most, a few hours in the monkey and usually a few days to about two weeks in man. The return of the eyes to a normal position may be due to the existence of a few uncrossed cortico-bulbar fascicles, or to a not well understood adjustment to the imbalance through cortical discharge, or to both factors.

It is certainly true that deviation of the eyes may be produced by stimulation not only of the frontal eye fields, the parieto-occipital eye fields (areas 17, 18 and 19), and even area 4, but also of other cortical regions which resemble second motor areas and often are parts of such an area. These last mentioned regions are to be discussed in a later paper.

Certain significant and not generally recognized relations of the abducens portion of the cortico-bulbar system may be emphasized. These are: (1) the gradual shifting of many of its fibers from the pyramidal system to the medial lemniscus as aberrant pyramidal fascicles throughout the course of the path from the midbrain to lower pontine levels; (2) the decussation of this abducens component at pontine regions before it swings dorsolaterad to reach the lateral and ventrolateral border of the abducens nucleus; and (3) its intimate relation, as it lies near the abducens nucleus, to the facial root and to the cortico-tegmental system from areas 18 and 19.

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PLATE 1

EXPLANATION OF FIGURES

5   A photomicrograph of a transverse Marchi section from the midbrain of a macaque (Macaca mulatta) in which the ventral subfield of the frontal eye field had been destroyed (p. 372). It shows fibers of the abducens component of the cortico-bulbar tract in the medial lemniscus (MED. LEM.). The degenerated fascicles in the cerebral peduncle (CER. PED.) are also, in part, cortico-bulbar fibers for this nucleus. × 12.

6   A photomicrograph from a lower pons level of the same brain illustrated in figure 5. The abducens component of the aberrant cortico-bulbar tract lies in the medial lemniscus (MED. LEM.). Some fascicles (X) of this aberrant system cross the midline and a very few non-aberrant fibers (Y) join them. × 12.