



# Localization of the human frontal eye fields and motor hand area with transcranial magnetic stimulation and magnetic resonance imaging

T. Ro<sup>\*,1</sup>, S. Cheifet, H. Ingle, R. Shoup, R. Rafal

*Department of Neurology and Center for Neuroscience, University of California, Davis & VAHCS, Martinez, CA, USA*

Received 24 February 1998; accepted 10 July 1998

## Abstract

We localized the neuroanatomical correlates for control of saccadic eye movements and for finger movements using a combined transcranial magnetic stimulation (TMS) and magnetic resonance imaging (MRI) approach. Two participants underwent TMS while performing an endogenous saccade task. The motor hand area was localized by TMS and the region anterior to it was mapped to identify the borders of a region where TMS produced delays in generating contralateral saccades. MRI scans were then obtained with fiducial markers placed over the motor hand area and 2 cm anterior to it, the common cortical region that produced saccadic delays in these two subjects. It was also shown that the structural anatomy of the hand area, physiologically defined by visible contractions of the contralateral hand following TMS, corresponded to the knob-like structure recently reported [18, 19]. These results demonstrate that TMS can be a precise, non-invasive tool for neuroanatomical mapping of cortical structures when combined with structural images of the brain. © 1999 Elsevier Science Ltd. All rights reserved.

*Keywords:* Frontal eye fields (FEF); Saccades; Transcranial magnetic stimulation (TMS); Magnetic resonance imaging (MRI); Motor cortex

## 1. Introduction

The frontal eye field (FEF) in man is a cortical structure that is presumed to be involved with generating saccadic eye movements. Although there is little doubt regarding the existence of this cortical module, there has been confusion over the exact location and function of the FEF. This confusion mainly arises from conflicting reports demonstrating that the FEF is involved with generating different types of eye movements and lies in different regions of the frontal lobes (for a review, see [12]). In the current investigation, we attempted to anatomically localize the FEF by combining the technique of transcranial magnetic stimulation (TMS) along with structural magnetic resonance images (MRIs) of the brain.

In a previous study conducted in our laboratory, TMS of the prefrontal cortex delayed contralateral endogenous saccades, but had no influence on reflexive visually guided saccades [16]. In that study a large, 9 cm circular coil was

used to ensure that stimulation of the FEF occurred. However, the use of this large coil may have resulted in stimulation of other regions of the frontal lobes involved with generating saccadic eye movements, such as the supplementary eye fields (SEF) and the dorsolateral prefrontal cortex [15]. It remains unclear, therefore, which frontal area or areas might have produced the delays in generating contralateral endogenous saccades. In the current investigation, TMS was conducted using a more focal coil while the subjects performed an endogenous saccade generation task. The main goal of this study was to anatomically localize, with TMS and MRI, the region of the frontal lobes involved with generating contralateral endogenous saccades. We predicted that the critical frontal region involved with these types of saccadic eye movements would be located near the precentral sulcus in the broadly defined area of the human frontal eye fields.

The hand area of the motor cortex is easily localized with TMS since stimulation over this area induces visible contractions of the contralateral hand. Because of the ease in identifying this structure, and also because it has been shown that localization of this structure with TMS is highly accurate [17], it provided an ideal anatomical landmark to serve as a reference for mapping the FEFs. Furthermore, a recent anatomical description for the

\* Corresponding author. Tel.: +44 171-391-1123; fax: +44 171-916-8517; e-mail: t.ro@ucl.ac.uk.

<sup>1</sup> Present address: Institute of Cognitive Neuroscience, Alexandra House, 17 Queen Square, University College London, Gower St, London WC1E 6BT, UK.

localization of the hand area with MRI has been reported [18, 19]. Another goal of the current investigation was to validate the correspondence between physiological and morphological markers for the human motor hand area.

## 2. Method

### 2.1. Subjects

After informed consent, two subjects participated in this experiment. Both reported having normal or corrected vision and no history of any neurological disorders at the time of testing. They had participated in other TMS studies, but had not been subjects in the previous eye movement study with TMS [16]. The first subject was a 23-year-old female and the second subject was a 29-year-old female. Both were paid for their participation. The TMS and eye movement recording phase of the experiment took place at the VA Clinics in Martinez, CA, U.S.A.

### 2.2. Eye movement recording

Eye position was monitored using an Applied Science Laboratories (Bedford, MA, U.S.A.) Eye-Trac 210 that was connected to the parallel port of the computer. The digital output from the eye movement monitor representing eye position was sampled at a rate of 1000 Hz and was recorded by the computer after each trial. Following the experimental session, the eye movement data were filtered with a 200 Hz low-pass filter. Saccadic eye movement latencies were identified and defined in this experiment as the point at which the velocity of the eye movement exceeded 50° per s.

### 2.3. Transcranial magnetic stimulation

Transcranial magnetic stimulation was performed using a Cadwell Laboratories (Kennewick, WA, U.S.A.) MES-10 stimulator. The MES-10 stimulator at maximum intensity creates a 2.2 Tesla field with a shape determined by the configuration of the coil [1]. A focal, figure-eight shaped coil, with each component of the figure-eight measuring 4.5 cm in diameter, was used throughout the experiment. Because the click associated with a TMS pulse may cause hearing damage ([4], but see [11]), all subjects wore sound attenuating earplugs during the study.

### 2.4. Apparatus, stimulus and procedure

An IBM compatible personal computer was used to trigger the MES-10, to record the eye position, and for stimulus presentation. Millisecond (ms) timing, used to trigger the MES-10 and to sample the eye position was

achieved by setting the 8253 chip of the computer to ms ticks. The computer was connected to a NEC Multisync video graphics array (VGA) stimulus monitor. The timing of the visual displays was controlled by the vertical synchronization of the computer monitor at 16.7 ms intervals (60 Hz).

Prior to the start of the experiment, localization of the hand area of the motor cortex, which was used to provide a scalp landmark, was performed using the figure-eight coil. With this coil positioned over the motor cortex, it was sometimes possible to obtain twitches from individual digits of the contralateral hand. After localizing the area of motor cortex that produced the most reliable, visible contraction of the contralateral hand at a suprathreshold TMS output intensity, a scalp marking was made with a grease pencil on each subject over this location. The TMS intensity was then decreased and coil position adjusted until a visible contraction of the hand was barely visible. This location and intensity setting was defined as the hand area motor threshold point.

TMS was then administered while subjects performed the eye movement task. TMS of sites in the rostral and caudal directions from the hand area of the motor cortex was conducted at 1 cm separations until an anterior and posterior border was found. Once these borders were obtained, the borders in the medial and lateral directions were then obtained in the same manner. In the first subject, stimulation of different sites in the right frontal lobe was initially conducted at a TMS intensity that was 10% above the motor threshold. Because the boundaries of the frontal eye fields using this intensity was difficult to map in the first session, the intensity for the subsequent testing sessions was decreased to the defined motor cortex threshold intensity. In the second subject, all stimulation over the left frontal lobe was conducted at the TMS threshold of the motor cortex.

The subjects were seated 57 cm from the computer monitor in a dimly and diffusely lit room. A small filled circle, measuring 0.1° in diameter, served as the initial fixation point and was presented in the center of the monitor until the start of each trial. Two unfilled squares that measured 1° on each side were used as marker boxes and were present throughout the experiment. These boxes were placed 10° to the left and right of the fixation point. Following an intertrial interval of 2000 ms, the fixation point was removed and a go signal immediately appeared. The go signal was an arrowhead that was presented in the center of the display. The arrowhead measured 1° in height and 0.5° in width. The direction of the go signal was randomly determined on each trial and was presented for 100 ms (Fig. 1). All stimuli were light gray on a black background.

In all blocks except for the no TMS control block, a TMS pulse was administered on each trial 50 ms before the onset of the go signal. This SOA setting was determined to be optimal in a pilot study conducted on these

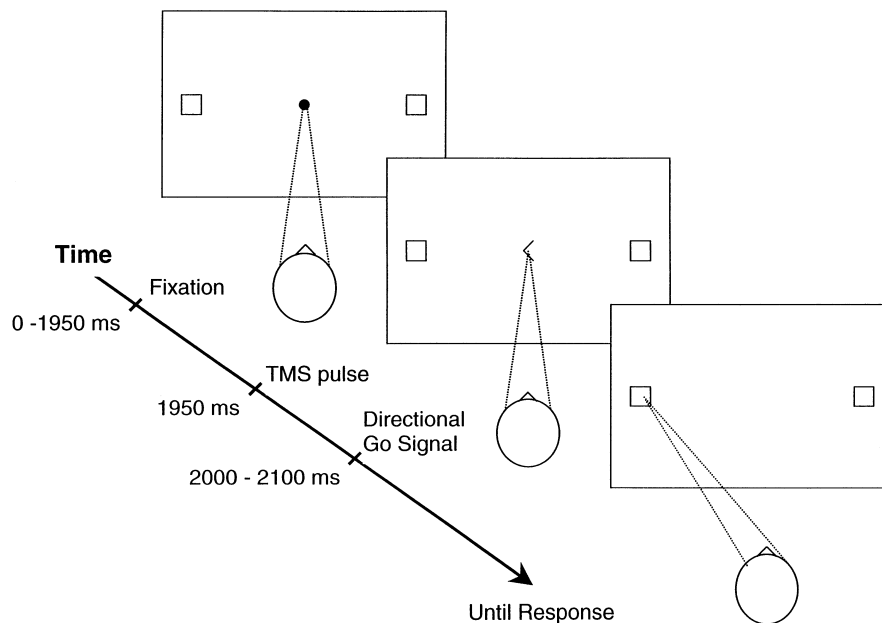


Fig. 1. Depicts an example of the sequence of stimulus events.

same subjects in which four different TMS pulse to go signal stimulus onset asynchronies (SOA) were used. The axis of the TMS coil was angled at approximately  $90^\circ$  from the mid-sagittal axis while the subjects sat upright and performed the eye movement task.

The subjects were instructed to keep their eyes on fixation until a go signal appeared. After the onset of the go signal, the subjects were instructed to make a saccade, as quickly and as accurately as possible, to the box that the arrowhead was pointing towards. Following the saccade, the subjects were told to return their eyes back to the fixation point. Subjects were asked to suppress blinks and to ignore the TMS pulse as best as possible.

Trials with saccades made in the wrong direction or with saccade latencies faster or slower than two standard deviations (SDs) from the mean were excluded from analysis. The right hemisphere TMS subject participated in a total of four testing sessions, each on separate days, since mapping the borders was more difficult in this subject. The left hemisphere TMS subject participated in one testing session. Within each session, blocks of trials were collected with the TMS coil positioned over different cortical locations for each block, except in the case of the no TMS block. The subjects completed 100 trials within a block, 50 trials for each eye movement direction.

Subsequent to the FEF mapping with TMS, two fiducial markers (gel-based Vitamin E capsules) were placed on the scalp overlying the brain tissue that when stimulated, (a) caused visible contractions of the contralateral hand, and (b) produced delays in generating voluntary saccades. An MRI scan was then taken of the brain with the high intensity markers to localize the brain anatomy

of the hand area and the area that delayed these types of eye movements.

### 2.5. Magnetic resonance images

The MRI scans were obtained using a 1.5 Tesla GE (Milwaukee, WI, U.S.A.) Signa magnet. The MRIs were obtained at the Magnetic Resonance Science Center at the University of California, San Francisco, U.S.A. A protocol was used that allowed the acquisition of 124 1.5 mm thick contiguous, T1 weighted, transaxial images.

Once obtained, the transaxial MRI images were converted into a 16-bit image volume file for subsequent processing on a Silicon Graphics (Mountain View, CA, U.S.A.) Indigo 2 computer using the VIDA software package (University of Iowa, Iowa City, U.S.A.). The volume file was then realigned such that each transaxial slice was parallel to the anterior commissure-posterior commissure line. All non-brain matter was then removed from the images and the slices were subsequently tiled to form a 3-dimensional volume reconstruction of the brain.

## 3. Results

The saccade latencies for contralateral and ipsilateral saccades that were no more or less than two standard deviations from the mean were subjected to a *t*-test. The results from the different TMS sites are graphically depicted in Fig. 2a and 2b for the right hemisphere and left hemisphere TMS subjects, respectively. Note the shape and structure of the hand area in each subject (blue

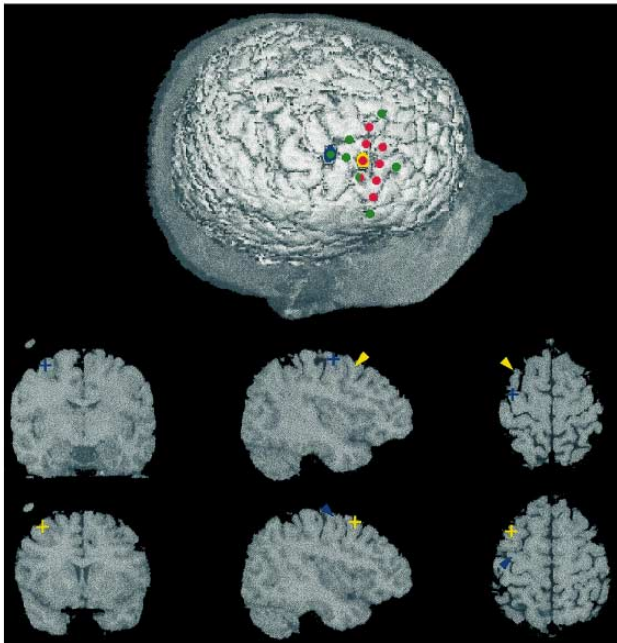


Fig. 2a. The locations of the TMS sites for the first subject. The blue crosshairs on the top row of images (and blue arrowheads on the bottom row) indicate the motor hand area as identified by TMS activation of the contralateral fingers. Note the correspondence to the backward hook of the motor hand area on the sagittal view (top row) and the epsilon shape on the transaxial view (bottom row). The yellow crosshairs on the bottom row (yellow arrowheads on the top row) indicate the position of the scalp marker placed 2 cm anterior to the hand area. This was the common area that produced increases in contralateral saccade latencies in both subjects. The top panel shows a 3-D volume rendered reconstruction in which the large blue and yellow blobs represent the locations of the fiducial markers. The smaller circles on this portion of the figure represent all of the locations that were stimulated. The small green circles are areas where no significant differences between contralateral and ipsilateral saccades were obtained, whereas the small red circles are the areas that when stimulated produced significant delays for generating saccadic eye movements in the contralateral direction.

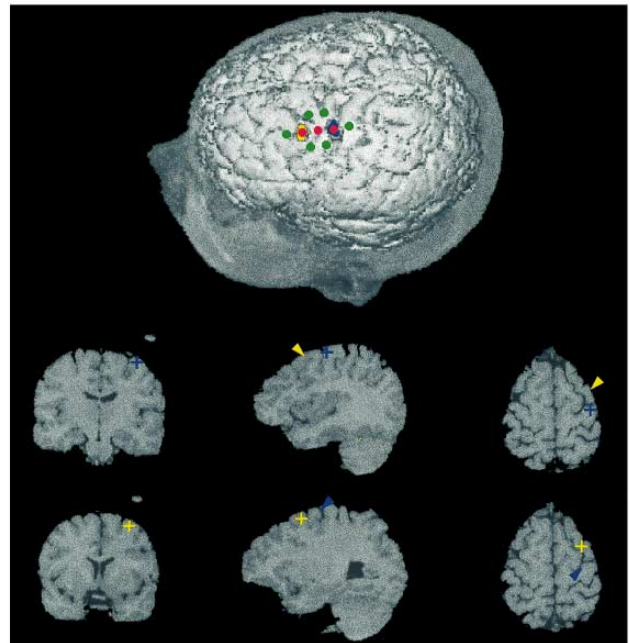


Fig. 2b. The locations of the TMS sites for the second subject. See legend of Fig. 2a for details.

crosshairs and arrows). The numerical data are presented in chronological order of testing in Tables 1a and 1b.

Although both subjects had more than one critical location that induced delays of saccadic eye movements when stimulated, both subjects showed delays when TMS was over the cortex 2 cm anterior to the hand area in the middle frontal gyrus. This was the location that was marked for the MRI scans. Overall, the right hemisphere TMS subject had a region with its posterior border located at the cortex approximately 1.5 cm anterior to the hand area. The anterior border for this subject was located 3.5 cm anterior to the hand area and the region extended approximately 5 cm in extent within the dorsal-medial plane (2.5 cm in either direction from the transaxial plane intersecting the hand area). The other subject had a more confined area extending from the region approximately 0.5 cm posterior to the hand area of the motor cortex to a location 2.5 cm anterior to the pre-

central gyrus. The dorsal-medial extent in this second subject was restricted to an area of approximately 1 cm (0.5 cm dorsal and 0.5 cm medial to the transaxial plane intersecting the hand area).

On the MRIs the hand area of the motor cortex (blue crosshairs and arrows in Fig. 2), as defined by physiological responses to TMS, had shapes that were consistent with the report by Yousry et al. [19]. On the sagittal cuts for both subjects, the hand area had a hooked shape structure. On the transaxial cuts, the hand area resembled an epsilon shape in the right hemisphere TMS subject, whereas in the left hemisphere TMS subject, the hand area resembled an inverted omega shape. Note that the corresponding slices in the different view planes in these figures all intersect one another.

#### 4. Discussion

In both subjects tested, there was more than one TMS site that induced delays in generating contralateral saccades. Although there were considerable differences between these two subjects, TMS of the cortex 2 cm anterior to the motor cortex lead to contralateral saccadic eye movement delays in both subjects. This descriptive location is consistent with the results from numerous positron emission tomography (PET) functional imaging studies on the FEF that also demarcate the location at 20 mm anterior to the hand area (for review, see [12]).

For the right hemisphere TMS subject, there was a considerable amount of variability within the coronal or dorsal-medial plane. This too is consistent with the report



Table 1a  
Mean saccadic latencies (RTs), standard deviations (SDs), percentage errors, and *P*-values for the different TMS sites in Subject 1

x, y	Contralateral			Ipsilateral			<i>P</i> -value
	RTs	SDs	Errors %	RTs	SDs	Errors %	
1, 0 (s)	219.8	(25.0)	0	217.8	(30.6)	10	0.727
2, 0 (s)	232.2	(25.6)	4	217.6	(26.2)	4	0.007
3, 0 (s)	223	(22.2)	2	210.8	(22.4)	6	0.009
2, 1 (s)	230.6	(16.0)	8	215.7	(20.3)	4	0.000
No TMS	233.3	(14.2)	8	228.9	(13.7)	4	0.127
2, 1 (s)	231.7	(19.0)	2	222.6	(20.8)	4	0.025
4, 0 (s)	226.9	(22.7)	4	219.2	(24.9)	4	0.112
2, 0	229.3	(16.3)	6	220	(21.0)	4	0.017
3, 0	230.5	(12.8)	6	221.1	(16.0)	2	0.002
2, 1	236.9	(18.0)	4	224.5	(16.1)	6	0.000
2, -1	223.9	(16.7)	4	216.9	(18.8)	4	0.056
3, 1	223.1	(13.6)	6	212.3	(18.9)	6	0.002
3, -1	219.6	(16.3)	2	212	(19.5)	8	0.039
1, 1	210.9	(19.7)	2	204.2	(22.2)	2	0.11
2, 2	215	(18.5)	6	205.1	(17.6)	8	0.01
2.5, 3	221	(14.9)	4	215.8	(25.0)	4	0.214
3, -2	237.1	(18.9)	4	223	(17.2)	2	0.000
3, -3	212.1	(13.9)	6	214	(14.6)	6	0.524

Coordinate 0, 0 represents the location of the hand area of the motor cortex. The other locations are denoted by how many centimeters from the hand area the TMS site was (x for deviations within the sagittal plane and y for deviations within the coronal plane). The 's' in parentheses represents the suprathreshold TMS blocks.

Table 1b  
Mean RTs, SDs, percentage errors, and *P*-values for the different TMS sites in Subject 2. See Table 1 for details

x, y	Contralateral			Ipsilateral			<i>P</i> -value
	RTs	SDs	Errors %	RTs	SDs	Errors %	
1, 0	260.1	(24.9)	2	245.9	(19.8)	4	0.003
0, 0	285.3	(42.3)	6	265.4	(26.5)	10	0.008
No TMS	284.2	(32.8)	6	278.7	(25.0)	4	0.634
-1, 0	237.2	(24.1)	4	233.7	(21.0)	8	0.534
2, 0	248.5	(26.6)	6	219.7	(20.1)	6	0.000
3, 0	242.6	(24.2)	8	233.5	(21.4)	4	0.054
0.5, 1	249.4	(24.4)	4	239	(29.1)	2	0.055
1.5, 1	244.8	(26.3)	0	247.1	(20.5)	2	0.641
0.5, -1	253	(19.1)	8	250.5	(23.7)	6	0.583
1.5, -1	237.9	(20.2)	6	234.7	(19.3)	4	0.553

by Paus [12] demonstrating that the variability in localizing this structure with PET is mainly within this plane. For the left TMS subject, however, there was a more restricted cortical region that when stimulated, produced delays in contralateral saccade generation. It is presently unclear what factors may contribute to the variability in size and location of the FEF, but it may be due to a left-right hemispheric difference or more simply with individual differences between subjects. Further research with larger sample sizes may provide insights into the possible bases for these differences.

One alternative for why there may have been as much

variability between the subjects could be based on the way that the hand area was localized in this study. Because visible twitches rather than electromyographic (EMG) recordings were used, it may be that the area that was determined to be the motor hand area was mislocalized to an area more rostral than the actual hand area in one of the subjects. Areas in the premotor cortex (e.g. dorsal premotor cortex or PMd) are known to have direct corticospinal connections [5–7] and TMS of these premotor areas may have induced visible contractions of the contralateral hand. If localization of the hand area was misplaced more rostrally, and to a further extent

in the second subject, then the actual correspondence between the area that delayed saccadic eye movements in these subjects might be greater. However, inspection of the structure defined to be the hand area was consistent between the two subjects and with the anatomical description reported by Yousry et al. [19]. Furthermore, not all of the effective sites in delaying contralateral endogenous saccades were simply shifted rostrally as there were larger differences between the subjects within the coronal plane. We therefore find the possibility of an unsystematic error in localization of the hand area to be unlikely.

In both subjects, the hand area marker appeared on the anterior portion of the precentral sulcus. An alternative explanation for why the hand area markers, and also the FEF markers, may have been slightly displaced rostrally in both subjects may be based on the positioning of the subjects during the different phases of the study. During the TMS phase, the subjects sat upright while during the MRI scan the subjects laid supine. The brain may have been slightly shifted towards the occiput when the subjects were placed in the MRI scanner. A similar account for the anterior placement of the hand area with TMS was reported by Wasserman et al. [17].

Recent studies in monkeys [2, 3] and in man [8, 10, 12, 15] have attempted to localize frontal regions subserving different forms of saccadic eye movements. However, many of these studies used vastly different methodologies and comparisons made between them may not be so informative regarding localization of the FEF. It may be that the frontal area involved in generating a saccadic eye movement may depend on the type of task that is used. For example the area localized as the FEF by Luna et al. [10], who used a more reflexive saccadic eye movement task with human subjects in a fMRI study, was placed further caudally than the placement in the current investigation. Chen and Wise [2, 3] report single units in the supplementary eye fields of monkeys that are involved with conditional eye movement responses. It may therefore be that the areas reported here as the FEF, and in other investigations attempting to localize this structure, are dependent upon the type of saccadic eye movement task that is employed. Accordingly, it may be that rather than localizing the FEF in the current investigation, we have localized a novel area that is involved with generating a specific type of endogenous eye movement response, and that may be different from other frontal areas involved with generating different forms of saccadic eye movements. Further research with more direct comparisons of complex types of eye movement tasks that are presumed to involve cortical control is required to validate this speculation.

In the left hemisphere subject, TMS of the hand area of the motor cortex also induced delays in contralateral saccades. However, the right hemisphere TMS subject did not show a consistent delay in making contralateral

saccades when stimulation was over the motor cortex. Penfield [13, 14] reported that eye movements could sometimes be elicited in certain patients with direct electrical stimulation of the exposed motor cortex. Taken together, these results suggest that the hand area of the motor cortex may be involved with generating eye movements. One plausible explanation for this result is that the hand area may be involved in integrating eye and hand movements during visually guided manipulation [9]. Though speculative, these results may suggest that visuomotor integration processes may arise from interactions between the primary motor cortex and the FEF, each of which can influence the generation of saccades.

In this study, structural localization of the hand area of the motor cortex was achieved. Our results are consistent with the recent study of Yousry et al. [19] demonstrating that the hook shaped structure on sagittal views and the epsilon or inverted omega shaped structure on transaxial views is an accurate locator for the hand area. The current investigation provides further converging evidence by showing that this morphologically defined structure elicits visible contractions of the contralateral hand when a TMS pulse is administered.

We have functionally localized the FEF and the hand area of the motor cortex using TMS combined with structural MRI scans. These results demonstrate that TMS is a useful and precise technique for mapping cortical anatomy when combined with a MRI obtained within the same individual. Future studies using this combined approach are aimed at localizing other structures in the brain that may be involved with generating shifts of gaze as well as structures involved with shifts of visual attention.

### Acknowledgments

This work was supported by US PHS grant MH41544 to R. Rafal. We thank the Magnetic Resonance Science Center, University of California, San Francisco, U.S.A. for their assistance in obtaining the MRI scans and Dr Eric Hoffman from the University of Iowa and the faculty and staff from the Center for Functional Imaging at Lawrence Berkeley Laboratory for providing the software for image analysis. We also thank Matthew Rushworth for valuable comments made on an earlier version of this manuscript.

### References

- [1] Cadwell J. Principles of magnetoelectric stimulation. In: Chokroverty S, editor. *Magnetic stimulation in clinical neurophysiology*. Boston, MA: Butterworths, 1990:13–32.
- [2] Chen LL, Wise SP. Neuronal activity in the supplementary eye field during acquisition of conditional oculomotor associations. *Journal of Neurophysiology* 1995;73:1101–21.
- [3] Chen LL, Wise SP. Supplementary eye field contrasted with the

- frontal eye field during acquisition of conditional oculomotor associations. *Journal of Neurophysiology* 1995;73:1122–34.
- [4] Counter SA, Borg E, Lofqvist L, Brismar T. Hearing loss from the acoustic artifact of the coil used in extracranial magnetic stimulation. *Neurology* 1990;40:1159–62.
- [5] Dum RP, Strick PL. The origin of corticospinal projections from the premotor areas in the frontal lobe. *Journal of Neuroscience* 1991;11:667–89.
- [6] Fink GR, Frackowiak RS, Pietrzyk U, Passingham RE. Multiple nonprimary motor areas in the human cortex. *Journal of Neurophysiology* 1997;77:2164–74.
- [7] He SQ, Dum RP, Strick PL. Topographic organization of corticospinal projections from the frontal lobe: motor areas on the lateral surface of the hemisphere. *Journal of Neuroscience* 1993;13:952–80.
- [8] Henik A, Rafal R, Rhodes D. Endogenously generated and visually guided saccades after lesions of the human frontal eye fields. *Journal of Cognitive Neuroscience* 1994;6:400–411.
- [9] Jeannerod M, Rossetti Y. Visuomotor coordination as a dissociable visual function: experimental and clinical evidence. *Baillieres Clinical Neurology* 1993;2:439–60.
- [10] Luna B, Thulborn KR, Strojwas MH, McCurtain BJ, Berman RA, Genovese CR, Sweeney JA. Dorsal cortical regions subserving visually guided saccades in humans: an fMRI study. *Cerebral Cortex* 1998;8:40–7.
- [11] Pascual-Leone A, Cohen LG, Shotland LI, Dang N, Pikus A, Wassermann EM, Brasil-Neto JP, Valls-Sole J, Hallett M. No evidence of hearing loss in humans due to transcranial magnetic stimulation. *Neurology* 1992;42:647–51.
- [12] Paus T. Location and function of the human frontal eye-field: a selective review. *Neuropsychologia* 1996;34:475–83.
- [13] Penfield W, Jasper HH. *Epilepsy and the Functional Anatomy of the Human Brain*. Boston: Little Brown. 1954.
- [14] Penfield W., Rasmussen, T. *The Cerebral Cortex of Man: a Clinical Study of Localization of Function*. New York, NY: Macmillan. 1950.
- [15] Pierrot-Deseilligny C, Israel I, Berthoz A, Rivaud S, Gaymard B. Role of the different frontal lobe areas in the control of the horizontal component of memory-guided saccades in man. *Experimental Brain Research* 1993;95:166–71.
- [16] Ro T, Henik A, Machado L, Rafal R. Transcranial magnetic stimulation of the prefrontal cortex delays contralateral endogenous saccades. *Journal of Cognitive Neuroscience* 1997;9:433–40.
- [17] Wasserman EM, Wang B, Zeffiro TA, Sadato N, Pascual-Leone A, Toro C, Hallett M. Locating the motor cortex on the MRI with transcranial magnetic stimulation and PET. *Neuroimage* 1996;3:1–9.
- [18] White LE, Andrews TJ, Hulette C, Richards A, Groelle M, Paydarfar J, Purves D. Structure of the human sensorimotor system. I: Morphology and cytoarchitecture of the central sulcus. *Cerebral Cortex* 1997;7:18–30.
- [19] Yousry TA, Schmid UD, Alkadhi H, Schmidt D, Peraud A, Buettner A, Winkler P. Localization of the motor hand area to a knob on the precentral gyrus. A new landmark. *Brain* 1997;120:141–57.