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RESEARCH NOTE

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MR-Eyetracker: a new method for eye movement recording in functional magnetic resonance imaging

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Abstract We present a method for recording saccadic and pursuit eye movements in the magnetic resonance tomograph designed for visual functional magnetic resonance imaging (fMRI) experiments. To reliably classify brain areas as pursuit or saccade related it is important to carefully measure the actual eye movements. For this purpose, infrared light, created outside the scanner by light-emitting diodes (LEDs), is guided via optic fibers into the head coil and onto the eye of the subject. Two additional fiber optical cables pick up the light reflected by the iris. The illuminating and detecting cables are mounted in a plastic eyepiece that is manually lowered to the level of the eye. By means of differential amplification, we obtain a signal that covaries with the horizontal position of the eye. Calibration of eye position within the scanner yields an estimate of eye position with a resolution of 0.2° at a sampling rate of 1000 Hz. Experiments are presented that employ echoplanar imaging with 12 image planes through visual, parietal and frontal cortex while subjects performed saccadic and pursuit eye movements. The distribution of BOLD (blood oxygen level dependent) responses is shown to depend on the type of eye movement performed. Our method yields high temporal and spatial resolution of the horizontal component of eye movements during fMRI scanning. Since the signal is purely optical, there is no interaction between the eye movement signals and the echoplanar images. This reasonably priced eye tracker can be used to control eye position and monitor eye movements during fMRI.

Key words Functional magnetic resonance imaging · Blood oxygen level dependent (BOLD) effect · Motion perception · Oculomotor pursuit

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Introduction

Binocular vision is characterized by frequent conjugate eye movements. These eye movements are either spontaneous in nature or they are visually guided (Fischer 1987). Visually guided eye movements fall into two general classes. Saccadic eye movements are ballistic in nature and direct the fovea to a target or location of interest. Pursuit eye movements are smooth continuous tracking movements, when the eyes pursue a moving target (Lisberger et al. 1987).

Single-unit recordings in trained monkeys have revealed several areas underlying saccadic and pursuit eye movements. Chief among these are the frontal eye fields (FEF; Bruce et al. 1985; Funahashi et al. 1991; Schall and Hanes 1993), and the supplementary eye fields (SEF) in the prefrontal cortex and areas MT/MST (V5/V5a) in the fundus and bank of the superior temporal sulcus of macaque monkey (Lisberger et al. 1987; Dürsteler and Wurtz 1988; Komatsu and Wurtz 1988).

Functional magnetic resonance imaging (fMRI) is now an established technique used to noninvasively map hemodynamic responses to sensory and cognitive stimulation in the human brain. T2*-weighted imaging reveals changes in blood oxygenation in cortical areas involved in the required neural processing (Ogawa et al. 1990, 1993; Kwong et al. 1992; Turner et al. 1993). Several studies have reported on the human V5/V5a complex in the occipital-temporal junction region (Tootell et al. 1995; Van Oostende et al. 1997; Smith et al. 1998) that responds selectively to motion. Selective changes in regional cerebral blood flow (rCBF) in response to visual motion stimulation had already been demonstrated in earlier positron emission tomography (PET) studies (Corbetta et al 1991; Zeki et al. 1991; Watson et al. 1993; Dupont et al. 1994; Cheng et al. 1995). In a recent study, Freitag et al. (1998) showed that the responses in V5/V5a can be enhanced when the subjects track the moving stimuli with their eyes. The frontal eye fields (FEF) and the supplementary eye fields (SEF) have been shown in a PET study to be in-

volved with the generation and execution of saccadic eye movements (Paus et al. 1995; Sweeney et al. 1996). Evidence from an fMRI study points to a different topography of responses in the FEF, depending on whether the subjects perform saccadic or smooth pursuit eye movements (Petit et al. 1997).

All of the studies presented thus far have been limited with respect to the ability to monitor eye movements in the functional imaging experiment. Electro-oculographic methods (Felblinger 1996; Freitag et al. 1998) are limited in resolution and the electrical signals can interact with the echoplanar imaging (EPI) sequences. To classify an activated brain area as pursuit or saccade related it is, however, necessary to know which eye movements actually occurred during stimulation. Pursuit runs contaminated with saccades can then be identified as such and any resulting coactivation of pursuit- and saccade-related brain areas can be determined. Since catchup saccades during pursuit can be rather small, the eye tracker system must have a good spatial and temporal resolution.

We present a new method of recording eye movements in the magnetic resonance scanner that is based on infrared light reflection. Using optic fiber cables to guide the infrared light into the headcoil and onto the eye of the subject, we can obtain a high-resolution signal that covaries with the horizontal position of the eye. Differences in the distribution of the BOLD (blood oxygen level dependent) response in dependence on the type of eye movement performed (saccades vs pursuit) suggest differences in the cortical networks involved in the two types of eye movements. Our method provides an accurate estimate of the eye position during fMRI experiments.

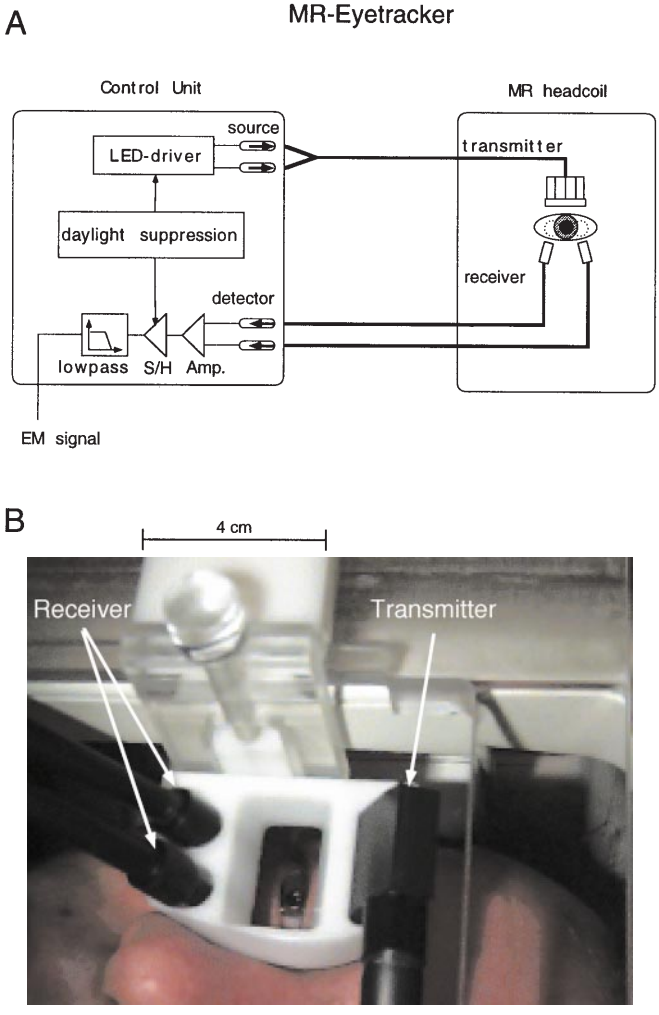


Fig. 1 **A** Schematic illustration of the MR-Eyetracker. For more details see text. **B** Photograph showing a subject positioned in the headcoil. The white plastic eyepiece is lowered into position, while the subject views the stimulus display through the rectangular window. The black tubes contain the optic fibers for the IR-light emittance and the IR-light detection

Materials and methods

MR-Eyetracker

Figure1A,B depicts the device used to monitor eye position in the MR scanner. We used optic fiber cables (Fiber Tec, Faseroptik GmbH, Waldkirch, Germany) which had a length of 5 m. The light-emitting source (two Siemens SFH 485-2 light-emitting diodes, LEDs; wavelength 880±20 nm; half angle ±20°; Siemens Components 1995, pp. 7–37) was guided by a fiber bundle (2×5 mm diameter), whereas the reflected light was picked up by two cables of 5 mm diameter each. Two Siemens SFH 203 FA diodes (Siemens Components 1995, pp. 8–40) served as photodetectors (maximum photosensitivity wavelength 900 nm; half angle ±20°; with daylight filter). The photodiodes were coupled DC to a differential current amplifier, a method basically described elsewhere (Gauthier and Volle 1975; Carpenter 1988; Reulen et al. 1988). The system works with a daylight suppression technique, such that IR light emission is chopped at 10 kHz, thereby prohibiting interference from ambient light. The signal bandwidth is 3 kHz after filtering with a Bessel fourth-order lowpass filter.

Standard fiber optics were used, in which each fiber had a diameter of 70 µm and the bundle had an opening angle of 65°. Light transmission was 57% at 900 nm (energy loss at entrance and exit of fibers), with an additional damping of 0.2 dB/m. The resultant output at the eye corresponded to <7 mW. For illumination of the eye, the fiber bundle was split at one end and each half picked up infrared light from one LED. At the eyepiece, the interleaved fibers form a horizontal array measuring 20×2 mm to illuminate the eye. The receiver cables were aligned to the nasal and the temporal limbus of the eye to transfer back the reflected IR light to the two photodetectors. The cables were encased in black malleable plastic. Figure 1B shows the plastic eyepiece into which the fiber optics were mounted. This eyepiece was attached to the frame of the mirror, which was used by the subject to view the screen. As it was designed to be lowered into the window of the headcoil, only a few centimeters of additional space was required.

Pilot measurements on water phantoms indicated that the cables had no effect on field homogeneity. Contrary to EOG recordings (Felblinger et al. 1996), our IR-reflection technique exhibits no interaction with the magnetic gradients. The difference signal between the inputs of the two detecting cables was amplified to a range of ±5 V. This signal was fed into a analog-to-digital converter (ADC) and stored on a computer hard disk. A multichannel display program (LabVIEW, National Instruments, Austin, TX) was used to acquire and display the signals derived from the MR-Eyetracker. Additional signals were recorded and displayed with regard to the stimulus position. The MR scanner provided a TTL pulse at the beginning of each volume acquisition and this pulse was used to trigger both our stimulation and eye movement acquisition programs. Calibration of eye position within the scanner in-

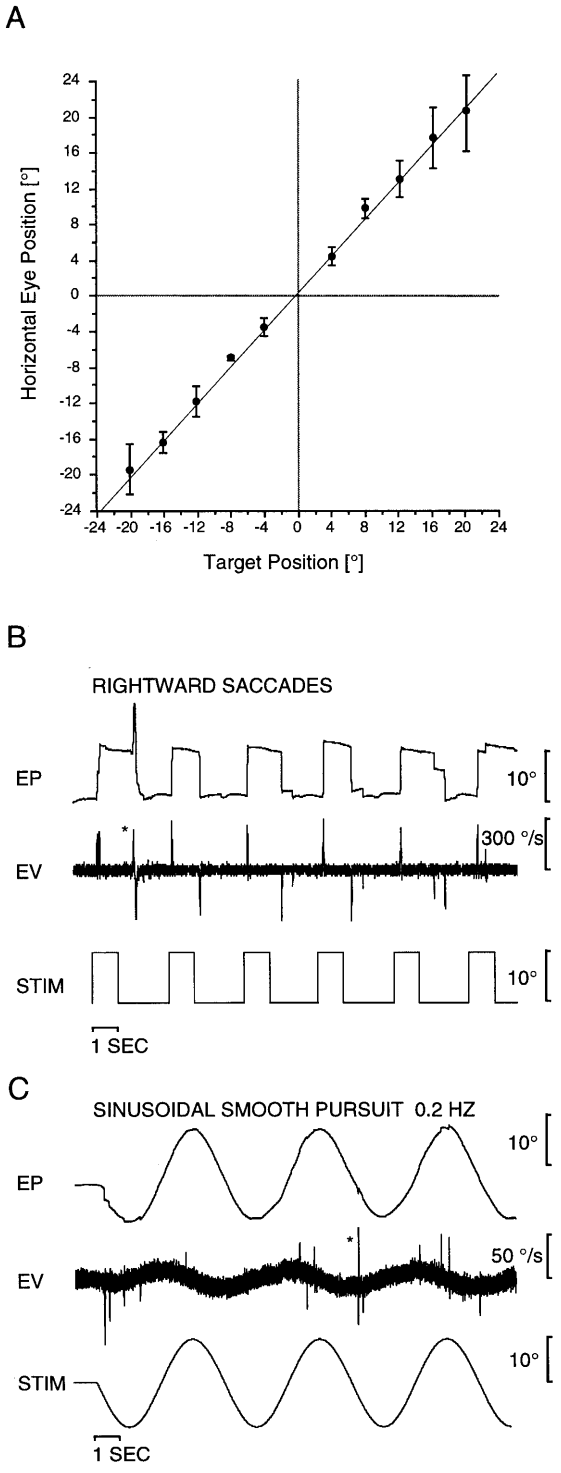


Fig. 2 **A** Horizontal eye position as a function of target position measured in a calibration run. The data points show the mean estimated eye position (in degrees) and the error bars show ±2 SE of the mean (95% confidence interval). The subject was positioned in the headcoil and performed saccadic eye movements to targets presented on a screen (viewed via a mirror). Note that the variability increases with increasing distance from the center. The measured range extended ±20°, which is greater than that used in the MR scanner (±15°). **B** Eye position (*EP*), eye velocity (*EV*) and stimulus position (*STIM*) shown over time (in seconds) for a task demanding saccadic eye movements. These results were obtained during MR scanning. **C** As in **B**, except that the subject performed a smooth pursuit task. *Asterisks* denote eye blinks

dicated a resolution of 0.2° (corresponding to the standard deviation of the signal during the fixation periods after any eye blinks and saccades were removed). Deviation from linearity for ±20° was less than 5%, which was determined in calibration runs (Fig. 2A).

Magnetic resonance imaging

Magnetic resonance imaging was performed with a 1.5-Tesla Siemens Magnetom Vision clinical scanner equipped with an EPI booster for fast gradient switching (Siemens, Erlangen) and a full-head radiofrequency (RF) receive-transmit headcoil. High-resolution, sagittal T1-weighted images were acquired with the MP-RAGE (magnetization prepared, rapid acquisition gradient echo) sequence to obtain a three-dimensional anatomical model of the head and brain. We defined the anterior-posterior commissural (AC-PC) plane (Talairach and Tournoux 1988) and reported all findings in this coordinate system. Shimming was performed for the entire brain using an autoshim routine, which yielded satisfactory magnetic field homogeneity.

Functional imaging was performed with T2*-weighted gradient recalled echoplanar imaging (EPI). The technical data for the functional measurements were TE 66 ms, TR 3 s, flip angle 90°, field of view 256 mm, matrix 128×128, resulting in a voxel size of 2×2×4 mm. The stimulation protocol consisted of twelve 30-s intervals with six alternating periods of rest (off) and stimulation (on). This protocol yielded 125 echoplanar volumes acquired over a 6-min period.

To minimize head motion, the subject's head was fixed with a vacuum cap, which was secured by temple rests within the headcoil. Despite these precautions, residual head motion was still evident in some of the image data. In-plane motion could be corrected by applying an image alignment algorithm (IMREG, Cox 1996). Excessive out-of-plane motion could not be corrected by this algorithm. However, we were able to detect such head motion and the images affected were removed from further analysis. The effects of the gradient noises were reduced by either ear plugs or sound-dampening headphones.

Visual stimulation

The subjects viewed the stimuli with a mirror adjusted to allow a maximum field of view. The stimuli were created on a Visual Stimulus Generator graphics card (Cambridge Research Ltd.) and projected (LCD projector, Panasonic) onto a transluminant screen which was mounted at the back of the gantry. The image subtended 30×24° of visual angle (800×600 pixels) at a viewing distance of 1.3 m.

The stimulus consisted of a bright-red square (0.5°), which was displayed on a uniform (saccades) or a static, random noise background (pursuit; see Fig. 2). The mean luminance of the display was constant throughout at 100 cd/m^2. The red square was positioned in the center of the display at the beginning of each run. Two different conditions were performed: a saccadic eye movement task and a pursuit task. During the saccadic eye movement task, the red square was extinguished 200 ms prior to the onset of a peripheral (10° left or right) target. The subject was asked to make a saccade as quickly as possible to the target location. In the pursuit task, the red square moved with a velocity that varied sinusoidally at a frequency of 0.2 Hz. The maximum speed was 12.6°/s. The total displacement was 10° left and right of the center. The subjects were requested to track the moving dot with their eyes. During the rest period, the red square was always present and located in the center of the display.

During the scans, we typically observed some eye blinks, but the frequency was similar for both baseline and stimulation periods. The eye movement signals during both saccade and pursuit task clearly indicated that the subjects followed the instructions. We also monitored any undesired eye movements during the fixation task and the baseline periods, which only occurred infrequently.

Table 1 Mean amplitude of saccades (*Amp*) and frequency of occurrence of saccades during single consecutive stimulation periods (*Period*). Each period consists of a 30-s off (i.e., fixation) period, followed by a 30-s on period. Data are shown for one subject in the pursuit and in the saccade task. In both cases only five (instead of six) stimulation periods were obtained. In the pursuit task, period 3 (*), there is an increase in the frequency of saccade occurrence and an increase in mean saccade amplitude in the on phase as compared to the off phase. Therefore pursuit- and saccade-related areas might be coactivated in this period. In the saccade task, period 4 (**) frequency of saccade occurrence and mean amplitude of saccades are comparable in the off and on phase. Therefore no differential activation of saccade-related areas is expected in this period

Period	Pursuit task				Saccade task			
	Off (Fixation)		On		Off (Fixation)		On	
	Amp (°)	Frequency(*n*/s)	Amp (°)	Frequency (*n*/s)	Amp (°)	Frequency (*n*/s)	Amp (°)	Frequency (n/s)
1	1.1	0.07	0.9	0.67	1.2	0.03	7.2	0.87
2	1.0	0.47	0.9	1.07	3.0	0.30	7.8	0.75
3	0.3	0.03	1.2	0.73*	3.4	0.33	6.2	0.88
4	0.9	0.17	1.1	1.00	9.2	0.86	6.7	0.81**
5	1.6	1.43	1.0	0.73	4.3	0.12	6.3	0.97

The data were analyzed and visualized using *BrainTools* developed by Dr. K. Singh (http://psyserver.pc.rhbnc.ac.uk/vision/BrainTools.html). The motion-corrected data were analyzed using a correlation method based on methods established by Bandettini et al. (1992) and Friston et al. (1995). The time course of the BOLD response profile was correlated with the on/off cycle of visual stimulation. To reduce noise, spatial smoothing of the functional signal within each slice was performed by convolution with a two-dimensional gaussian function (Friston et al. 1995) with a standard deviation of 1.7 mm. The time course of each voxel was correlated with a smoothed periodic function (squarewave convolved with a gaussian; time constant 6 s; cf. Friston et al. 1995). The time course of each voxel was also smoothed with a gaussian (time constant 6 s).

After giving their informed consent, six volunteers participated in the study. The subjects' age ranged from 24 to 37 years, mean age 29.3 years. One volunteer was left handed, the remaining five were right handed.

Results

A typical time course of eye position is shown for a saccade task (Fig. 2B) or the pursuit task (Fig. 2C). Although there is some high-frequency noise (50-Hz mains, picked up by the electrical cables) in the traces, there is a clear difference between the time course for the two types of eye movement. We determined the eye velocity offline. Although the signals are somewhat noisy, even small saccades were still visible as spikes on the velocity trace. Furthermore the velocity cosine of the eye position sine is visible (Fig. 2C).

Quantitative analysis of eye movement data revealed generally good performance of all subjects during both pursuit and saccade tasks. Occasional stimulation periods were contaminated by too many saccades that occurred either in the pursuit period or in the fixation period (Table 1).

All subjects showed significant activation in V1/V2 in both hemispheres during the saccade and pursuit tasks. Additional activation was found in the human V5/V5a complex located at the temporal occipital junction in BA 37 (x=42, y=–72, z=±4 mm), and this activation was most pronounced during the pursuit task. Figure 3 presents the results of one subject for the condition with saccades (Fig. 3A) and pursuit (Fig. 3B). In support of earlier work (Freitag et al. 1998), we found a significant increase of activation during periods with eye movements compared to periods with fixation. Both saccades and pursuit are associated with an activation in the frontal eye fields (for the example shown, FEF; x=30, y=–1, z=42 mm; cf. Fig. 3B,C).

It could be argued that the information gained by monitoring eye movements in the scanner does not justify the additional time and cost required. However, our results presented in Table 1 suggest that subject compliance cannot be taken for granted. To emphasize this point, we performed post hoc analysis of the BOLD response together with the recorded eye movement data during a saccadic task (see "Materials and methods"). The results of this analysis are shown for one subject in Fig. 4. The region of interest (ROI) shown here is the right frontal eye field (FEF), and the time course in Fig. 4B indicates a reasonable correlation between the average saccadic activity (defined as the product of saccade frequency and mean amplitude) and the resultant changes in the T2* signal over FEF. Note that the subject made a significant number of saccades during the next-to-last rest period. During this period the BOLD signal remains at an elevated level.

Fig. 4 A Axial T1-weighted anatomical image with functional overlays showing significant activation over the frontal eye fields (*FEF*) in prefrontal cortical area 6. Note the posterior activation of parietal areas. The Talairach coordinates are presented. **B** Relative change in T2* signal as a function of time (*red curve*) during the scan period. *Gray columns* signify the stimulation periods (saccadic task) and *white columns* give the rest periods (fixation on homogeneous background). *Black curve* (*and right ordinate*) depicts the integrated saccadic activity. Values are given in terms of the standard (z) scores, where 0 corresponds to the mean and +1 to 1 SD above the mean ▶

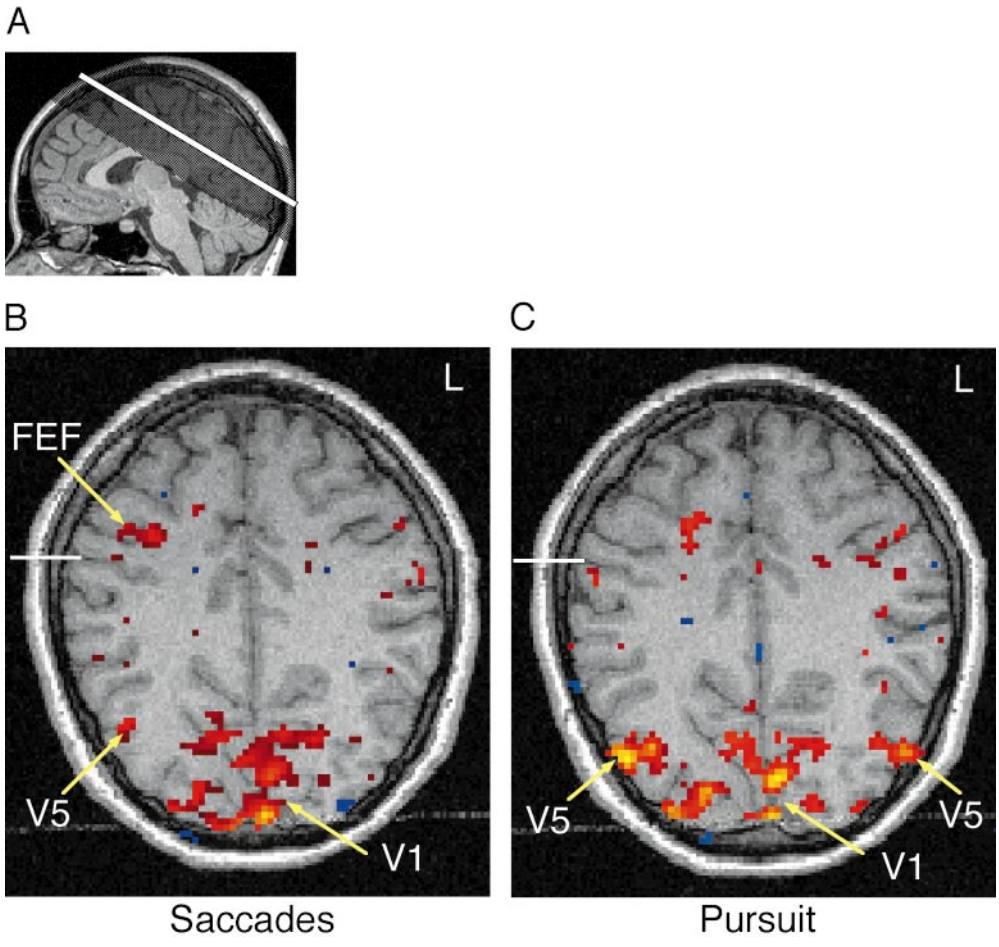
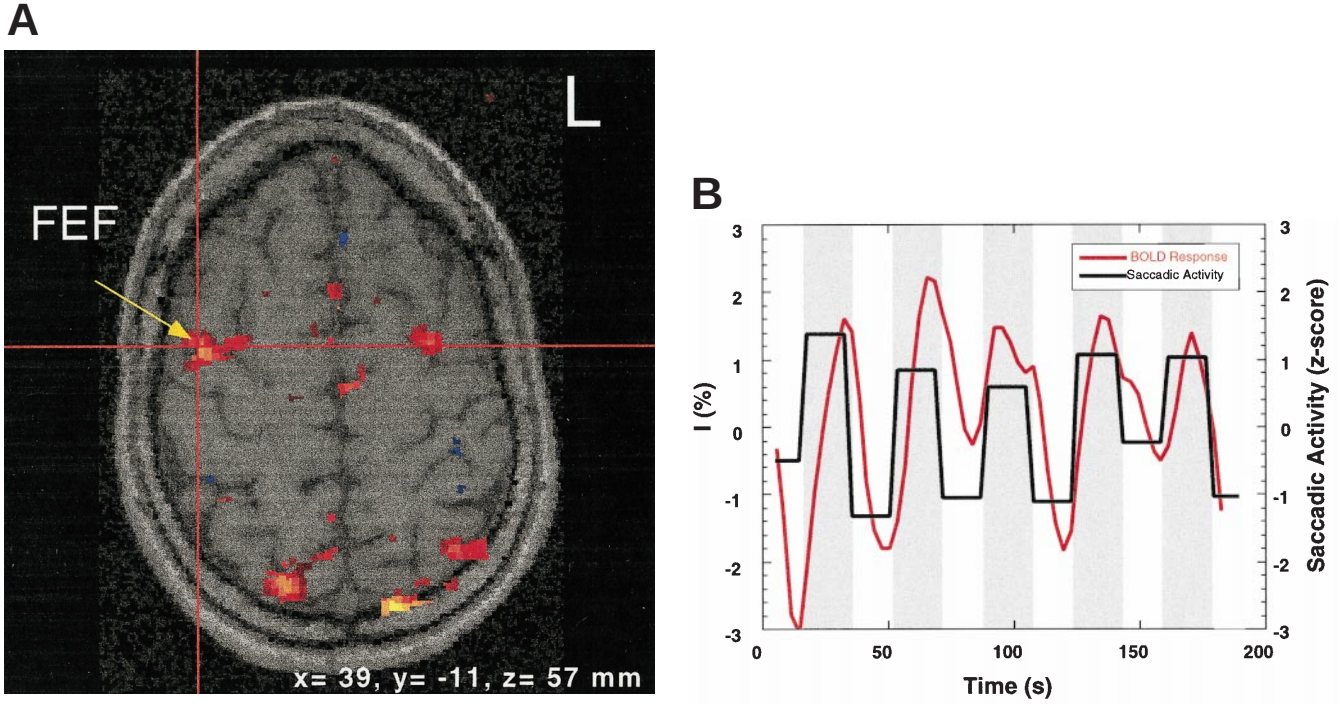


Fig. 3 **A** Sagittal scout depicting the volume (*gray hatched area*) and slice (*white line*) orientation. **B** Axial T1-weighted anatomical images with functional overlays depicting significant activation during the saccadic eye movement task. **C** Functional activations found during the pursuit task, otherwise as in **B**. The results are shown for one subject. Significant activation measured in terms of *z* scores are color coded (*red*, z=3.0; *orange*, z=4.0; *yellow*; $z \geq 5.0$)



Discussion

In this study, we present a new method for recording eye movements in the MR scanner. The results indicate that the proposed method has a high resolution. The MR-Eyetracker is capable of differentiating between saccades and smooth pursuit, and as such represents an important improvement over EOG-based recording systems in the fMRI setting. The method can be easily adjusted for individual scanners and can be used in conjunction with visual stimulating displays (e.g., LCD-based projectors). Offline analysis of the raw eye movement data can provide critical information on the subject's oculomotor behavior during the measurement periods. The resolution, linearity and replicability of the results are comparable to those reported for other IR-eye trackers. One important prerequisite is the complete immobilization of the subject's head in the headcoil. We used a vacuum cap to partially fix the head, but some residual head movements were still evident. Although the effects on the MR images of such subject motion can be corrected by the image registration software, it will limit the accuracy of the estimated eye position.

We compared the distribution of BOLD contrast effects evoked during saccadic and smooth pursuit tasks. The results indicate that the frontal eye fields (FEF), located in BA 6 in the precentral sulcus, are activated by both types of task. The saccade-induced activation appears to be somewhat more pronounced than the pursuit-induced activation. It has been recently reported (Petit et al. 1997) that activation evoked in the FEF during pursuit is located more laterally and inferior to that evoked by saccades. However, it should be noted that these authors did not monitor eye movements during the fMRI acquisition periods. Thus, the extent to which the pursuit could have been contaminated with saccades (especially considering the high stimulus velocity of 25°/s and the temporal waveform of stimulation-triangular position trace over time versus sinusoidal in the present study; cf. Fig. 2C) is left unknown. We observed considerable overlap in the distribution of BOLD signals during the two types of task. The mean position±1SD averaged over all subjects corresponded to the following values:

Pursuit: $|x|$=47.4±5.9, y=–3.6±6.6, z=44.0±8.9 mm
Saccadic: $|x|$=48.7±3.4, y=–3.2±6.5, z=42.3±6.7 mm

Compared to Table 1 in the Petit et al. study, our activations are slightly more anterior (approx. 10 mm) and slightly more lateral (5–15 mm). We observe, however, no shift in location across tasks. Obviously, more data would be required to resolve this issue.

Activation in the lateral occipitotemporal cortex (V5 or MT) has been found to be stronger during pursuit of a single dot as compared to fixation of a stationary dot on a moving grating (Barton et al. 1996), although the latter generated more retinal image motion. Barton et al. (1996), however, did not monitor eye movements within the scanner. As a consequence, they could provide only indirect information on the quality of the pursuit and to what extent saccades occurred during the pursuit task. The authors concluded that extraretinal signals (such as attention, efference copy, and pursuit command) enhance the activation in V5. Freitag et al. (1998) measured EOG with carbon electrodes and could monitor the extent to which the subjects fixated or moved their eyes. The EOG signal in their study was too noisy to extract an exact signal on eye position and eye speed. Despite these limitations, these authors also report that V5/V5a is more activated during the pursuit task compared to fixation, although the retinal motion is reduced. Our findings support both those of Barton et al. (1996) and Freitag et al. (1998) with respect to the role of V5/V5a in the control of smooth pursuit eye movements. The contribution of extraretinal signals to the BOLD response in human V5/V5a during pursuit remains a subject for further investigation. A challenge for future research would be to dissociate the effects of attention (Beauchamp et al. 1997; O'Craven et al. 1997) and pursuit command from those of the eye movements per se. Event-related paradigms (Buckner et al. 1996) could provide a direct means of comparing trials containing different types of eye movements, so that the different oculomotor parameters (frequency, amplitude, direction, etc.) could then be used as criteria for post hoc analyses of BOLD responses.

In summary, we have presented a new method of recording eye movements in the MR scanner. The optical fiber-based system is fairly easy to employ and can, with proper calibration, provide a reliable eye position signal during functional MRI experiments. We presented examples from saccade and pursuit tasks, which point to different distribution of BOLD responses. The results suggest that monitoring eye movements during fMRI experiments is an important source of information on subject behavior.

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