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The effect of saccadic eye movements on the sensor-level magnetoencephalogram

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HIGHLIGHTS

- The MEG signal elicited by the rotating eye dipoles is band-limited to below 30 Hz.
- The MEG signal created by the extraocular muscles are primarily monophasic pulses but they can be biphasic.
- For real data independent components need not clearly isolate the saccadic artifact.

ABSTRACT

Objective: We used a combination of simulation and recordings from human subjects to characterize how saccadic eye movements affect the magnetoencephalogram (MEG).
Methods: We used simulated saccadic eye movements to generate simulated MEG signals. We also recorded the MEG signals from three healthy adults to 5° magnitude saccades that were vertical up and down, and horizontal left and right.
Results: The signal elicited by the rotating eye dipoles is highly dependent on saccade direction, can cover a large area, can sometimes have a non-intuitive trajectory, but does not significantly extend above approximately 30 Hz in the frequency domain. In contrast, the saccadic spikes (which are primarily monophasic pulses, but can be biphasic) are highly localized to the lateral frontal regions for all saccade directions, and in the frequency domain extend up past 60 Hz.
Conclusions: Gamma band saccadic artifact is spatially localized to small regions regardless of saccade direction, but beta band and lower frequency saccadic artifact have broader spatial extents that vary strongly as a function of saccade direction.
Significance: We have here characterized the MEG saccadic artifact in both the spatial and the frequency domains for saccades of different directions. This could be important in ruling in or ruling out artifact in MEG recordings.

1. Introduction

For both electroencephalography (EEG) and magnetoencephalography (MEG) eye movements are a major signal source which could easily be confused with other brain-related signals. There are two primary factors which we consider here: the rotation of the eye dipoles, and the synchronous activation of the extraocular muscles.

Each eye acts like a strong current dipole, and its rotation due to saccadic eye movements can produce massive electrical and magnetic signals. This is the source of the electro-oculogram (EOG), but this signal is strong and can be easily seen at sensors across a large fraction of the scalp surface and not just near the eyes.

At the beginning of a saccade there is also a short-duration synchronous activation of the extraocular muscles (Van Gisbergen et al., 1981). This results in the so-called "saccadic spike," a brief transient at the beginning of a saccadic eye movement that has a frequency composition extending up into the gamma band (Boylan and Doig, 1989; Keren et al., 2010; Kovach et al., 2011;

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Moster and Goldberg, 1990; Riemslag et al., 1988; Thickbroom and Mastaglia, 1985; Yuval-Greenberg et al., 2008). This saccadic spike can be seen in human patients that have intact extraocular muscles moving a prosthetic eyeball (Thickbroom and Mastaglia, 1985), thus ruling out any sort of retinal or other eyeball-localized source.

Thus, eye movements can have strong effects on extracranial electric and magnetic recordings, and a clear understanding of how eye movements affect EEG and MEG signals is critical for interpreting these measures of brain function. Because of the recent interest in gamma-band brain activity, and because saccade timing and incidence can vary with the cognitive task, *even on non-visual tasks*, and *even when the eyes are closed*, (Ehrlichman et al., 2007), the properties of the saccadic spike are of especial current relevance.

As mentioned previously, there are extensive studies on the effects of saccadic eye movements on the EEG, but relatively few on the MEG. One recent study on the effects of saccades on the MEG found that the saccadic spike artifact in the MEG (which is sometimes but not always referred to in the MEG as the "spike field") was most prominent in the gamma frequency band, and as expected localized to the extraocular muscles (Carl et al., 2012). However, that study only examined horizontal saccades, aligned saccade onsets using the EOG instead of an eye tracker, used bandpass filtering to isolate the saccadic spike, and averaged their data over multiple subjects. In this study we looked at both horizontal and vertical saccades in both directions in individual subjects, modeled the effect of rotating eye current dipoles on the MEG signals, and did not use either narrow bandpass nor line noise notch filters to identify saccadic spike artifacts in the time domain.

We find that the saccadic spike artifact is typically a monophasic pulse, although it can sometimes be strongly biphasic. It begins before the start of a saccadic eye movement, and can extend up past 60 Hz in the frequency domain. In contrast, the effect of the moving dipoles in the frequency domain is primarily below 30 Hz (going down to alpha, theta, and lower frequencies), and has a more widespread spatial distribution that varies strongly with the direction of the eye movement. We also find that the effects of rotating eye current dipoles can in principle be completely accounted for with only three independent components, although in practice this is not so simple. These results may prove useful for ruling in or ruling out saccadic artifacts in MEG recordings, especially as visual inspection of the raw data from individual subjects remains such an important aspect of MEG studies.

2. Materials and methods

2.1. Simulations: single saccades

When an eye moves during a saccade, it can be modeled as a single rotating current dipole. The rotating current dipole creates a rotating magnetic field. As the rotating magnetic field sweeps across magnetometer sensors that are located at different positions around the head, it is possible that the magnetic field as a function of time that is picked up by any given magnetometer may not be a simple scaled version of the eye position as a function of time. Determining the possible effect of the geometry of a rotating eyeball on the signals picked up by fixed magnetometers is therefore critical to understanding how saccades may affect the recorded MEG signal.

Of course in the real world current must flow in continuous loops: it is impossible to have a single isolated segment of flowing current without there also being *return* currents. So if the eye is modeled as a current flowing from the front of the eye to the rear, there must also be currents flowing in the orbit and surrounding tissue that is moving from back to front. As is common practice we assume here that the return currents are so dispersed that they can be ignored. It is conceivable that the return currents may change their distribution due to a change in the relative position of the cornea in the orbit, which may add second-order effects, but this possibility is not explored here.

We took the positions and orientations of the magnetometers from the manufacturer-supplied coordinates of the 4-D Systems Magnes 148 WH MEG system. We modeled the two eyes as unit current dipoles at coordinates X (anterior–posterior) 80 mm, Y (medio-lateral) 32 mm, and z (superior–inferior) 25 mm for the left eye, and XYZ 80, −32, and 25 mm for the right eye (simulated intraocular distance 64 mm). We varied these positions over a range of ±3 cm anterior–posterior and ±2 cm superior–inferior to verify the robustness of the results.

The saccades were simulated using as a basis the change in angular position over time of the human critically damped 12° saccade of Bayhill et al. (1975). It was surprising to us that we were unable to find any other plots of angle vs. time for normal human saccades: for now, Bayhill et al. (1975) may be the only such example in the published literature, and we use it as a reference standard. For every millisecond of the saccade simulation, both the left and the right eye dipoles were each rotated by the same amount as the saccade from Bayhill et al. (1975) at that point in time. This rotation was performed in the horizontal plane for simulated horizontal saccades, and in the vertical plane for simulated vertical saccades. The simulation was written in Matlab and run at discrete intervals of 1 ms. The magnetic field at each magnetometer was computed using the Biot-Savart law:

$$B \propto \frac{Idlxr'}{|r'|^3} \tag{1}$$

where B is the magnetic field, I is unit current, dl is a unit vector pointing in the direction of the eye, and r' is the full displacement vector from the eye dipole to the location of each magnetometer. The simulated magnetometer signal was computed by taking the dot product of the magnetic field at each magnetometer location with the magnetometer normal vector. The eye velocities are slow enough that magneto-quasistatic conditions are assumed.

We also performed simulations with different sized saccades and verified that, as one might expect, the effects of the rotating eye dipoles on the MEG signal scale linearly with the size of the eye movement for saccades less than 12° in magnitude.

2.2. Simulations: multiple saccades and independent components analysis

We used a simulation to determine how many ICA components would be required to handle the eye-dipole artifacts in a dataset where the eyes could move in any direction and over a large range of amplitudes. We first created a simulated set of horizontal and vertical eye movements, where saccades occurred at intervals of between 250 and 400 ms. Each simulated saccade was to a random position ±25° from the central position both horizontally and vertically. The simulation lasted five minutes (300,000 ms). The simulation parameters were as in Section 2.1 above, as was the process of going from simulated eye position to simulated MEG signals. The variance in this simulated data set will be completely due to eye dipole rotation, and therefore any method that can completely account for this variance could, in principle, completely eliminate this artifact.

The simulated MEG signals were high-pass filtered, and the FastICA algorithm used to extract independent components (Hyvärinen, 1999). As there are 148 simulated sensors for 300,000 ms, the input to the FastICA algorithm consisted of 148