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Occipital gamma-oscillations modulated during eye movement tasks: simultaneous eye tracking and electrocorticography recording in epileptic patients

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Abstract

We determined the spatio-temporal dynamics of cortical gamma-oscillations modulated during eye movement tasks, using simultaneous eye tracking and intracranial electrocorticography (ECoG) recording. Patients with focal epilepsy were instructed to follow a target moving intermittently and unpredictably from one place to another either in an instantaneous or smooth fashion during extraoperative ECoG recording. Target motion elicited augmentation of gamma-oscillations in the lateral, inferior and polar occipital regions in addition to portions of parietal and frontal regions; subsequent voluntary eye movements elicited gamma-augmentation in the medial occipital region. Such occipital gamma-augmentations could not be explained by contaminations of ocular or myogenic artifacts. The degree of gamma-augmentation was generally larger during saccade compared to pursuit trials, while a portion of the polar occipital region showed pursuit-preferential gamma-augmentations. In addition to the aforementioned eye movement task, patients were asked to read a single word popping up on the screen. Gamma-augmentation was elicited in widespread occipital regions following word presentation, while gamma-augmentation in the anterior portion of the medial occipital region was elicited by an involuntary saccade following word presentation rather than word presentation itself. Gamma-augmentation in the lateral, inferior and polar occipital regions can be explained by increased attention to a moving target, whereas gamma-augmentation in the anterior-medial occipital region may be elicited by images in the peripheral

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field realigned following saccades. In functional studies comparing brain activation between two tasks, eye movement patterns during tasks may need to be considered as confounding factors.

Keywords

fixational saccades; smooth pursuit; high-frequency oscillations; pediatric epilepsy surgery; *in-vivo* animation of event-related gamma-oscillations

INTRODUCTION

Intracranial electrocorticography (ECoG) recording is utilized in epilepsy centers, to localize brain areas activated in sensorimotor and cognitive tasks. In general, augmentation of task-related gamma-oscillations on ECoG (50 to 200 Hz) is considered to represent cortical activation elicited by a given task (Crone et al., 2006). A human study with ECoG sampled mostly from the frontal and temporal regions previously demonstrated that a task requiring voluntary saccades elicited sustained gamma-augmentation in the frontal eye field around the onset of eye movement (Lachaux et al., 2006). Studies using scalp EEG and ECoG recordings also demonstrated that ocular and myogenic artifacts derived from eye movements resulted in a transient gamma-augmentation of non-cerebral origin in the anterior temporal regions (Yuval-Greenberg et al., 2008; Kovach et al., 2011). Such artifactual gamma-augmentation was temporarily locked to eye movements occurring 200 to 500 msec following presentation of visual stimulus; the degree of such artifactual gamma-augmentation was most severe in the anterior temporal regions and least severe in the occipital regions (Jerbi et al., 2009; Keren et al., 2010).

It is still uncertain how occipital gamma-oscillations are modulated during an eye movement task. Due to the lack of sampling from the occipital lobe, none of previous human ECoG studies could determine the spatio-temporal dynamics of eye-movement-related gamma-oscillations involving the occipital regions. A recent study using simultaneous eye tracking and scalp EEG recording suggested the presence of event-related potentials originating from the occipital region 100 to 400 msec following the onset of saccade (Dimigen et al., 2009). Previous studies of monkeys using implanted microelectrodes showed that saccadic eye movements were accompanied by increased spiking rates in portions of V1, V2 and V4 neurons and a decrease in other portions of V1 neurons (Leopold and Logothetis, 1998; Martinez-Conde et al., 2000). Previous fMRI studies have suggested the presence of eye movement-related brain responses in the occipital lobe in addition to the frontal and parietal eye fields as well as Rolandic cortex (Bodis-Wollner et al., 1999). In these regions, therefore, gamma-augmentations are expected to be elicited by a voluntary eye movement task.

In this study, participants were instructed to follow a target circle intermittently and unpredictably moving from one place to another either in an instantaneous or smooth fashion during extraoperative ECoG recording. We tested the following specific hypotheses: (i) Presentation of target motion would elicit augmentation of cortical gamma-oscillations in lateral occipital sites as well as the parietal and frontal eye fields; (ii) Subsequent eye movement would elicit gamma-augmentation in other occipital sites; (iii) The degree of gamma-augmentation in occipital regions would differ between saccade and pursuit trials. If a difference in gamma-modulations existed between these trials, it would further support the notion that eye movement patterns should be taken into account as confounding factors in brain mapping studies comparing cortical activation between two tasks.

As a secondary analysis, three patients were asked to read a single word popping up on the screen. We tested the following hypothesis: (iv) involuntary saccades following word presentation (rather than word presentation itself) would elicit gamma-augmentation in the anterior portion of the medial occipital region (i.e., in the presumed primary visual cortex for the peripheral vision; Wong and Sharpe, 1999; Yoshor et al., 2007). A behavioral study found that involuntary saccades during attempted fixation are linked to enhanced visibility of peripheral visual targets (Martinez-Conde et al., 2006).

METHODS

Patients

The inclusion criteria consisted of: (i) patients with focal epilepsy undergoing extraoperative subdural ECoG recording as a part of presurgical evaluation at Children's Hospital of Michigan or Harper University Hospital, Detroit; (ii) ECoG sampling involving the occipital region; and (iii) measurement of ECoG amplitude modulations driven by the voluntary eye movement task described below. The exclusion criteria consisted of: (i) presence of massive brain malformations; (ii) visual field deficits detected by confrontation; and (iii) history of previous epilepsy surgery. We studied a consecutive series of five patients satisfying both inclusion and exclusion criteria (age range: 13 – 21 years; 3 females; Table 1). All patients had normal developmental milestones and normal uncorrected visual acuity. None of the patients had a seizure within two hours prior to the task. The study was approved by the Institutional Review Board at Wayne State University, and written informed consent was obtained from the adult patient and the guardians of the pediatric patients.

Subdural electrode placement

For ECoG recording, platinum grid electrodes (10 mm intercontact distance, 4 mm diameter; Ad-tech, Racine, WI) were surgically implanted (Figure S1 on the website). All electrode plates were stitched to adjacent plates and/or the edge of dura mater, to avoid movement of subdural electrodes after placement. In addition, intraoperative pictures were taken with a digital camera before dural closure, to confirm the spatial accuracy of electrode display on the three-dimensional brain surface reconstructed from MRI (Wu et al., 2011).

Extraoperative video-ECoG recording

Video-ECoG recordings were obtained during the tasks described below, using a 192-channel Nihon Kohden Neurofax 1100A Digital System (Nihon Kohden America Inc, Foothill Ranch, CA, USA). The sampling frequency was set at 1,000 Hz with the amplifier band pass at 0.08 – 300 Hz. The averaged voltage of ECoG signals derived from the fifth and sixth intracranial electrodes of the ECoG amplifier was used as the original reference. ECoG signals were then re-montaged to a common average reference (Wu et al., 2011). Channels contaminated with large interictal epileptiform discharges or visually-apparent artifacts were excluded from the common average reference. No notch filter was used. All antiepileptic medications were discontinued on the day of subdural electrode placement. Electrodes overlying seizure onset zones or MR lesions were excluded from further analysis. Surface electromyography electrodes were placed on the left and right deltoid muscles, and electrooculography electrodes were placed 2.5 cm below and 2.5 cm lateral to the left and right outer canthi.

Eye movement recording

Eye movements were recorded with an infrared video-based tracking system with a sampling rate of 50 Hz, a spatial resolution of <0.1°, and a gaze position accuracy of <0.5° (iView X RED, SensoMotoric Instruments, GmbH). Horizontal and vertical eye positions

were integrated into the ECoG Recording System via the analog output card. This procedure allowed us to review ECoG, electrooculography and eye position measures simultaneously (Figures S2 and S3 on the website).

Events of saccades and eye blinks were marked with help of BeGaze 2.2 software (SensoMotoric Instruments, GmbH), which has a built-in saccade, fixation, eye blink detector using a dispersion-based algorithm (Smeets and Hooge, 2003). Uni-directional gradual eye movements of a minimum duration of 250 msec, with a direction corresponding to the direction of a target smooth motion, were visually determined as a pursuit. We recognize the following methodological limitations: (i) our eye tracking system is not designed to detect involuntary saccades with amplitudes ranging less than 0.1° (Martinez-Conde et al., 2009) and (ii) the sampling rate of our eye tracking system indicates the existence of an uncertainty of 20 msec regarding the onsets of eye movements.

Task 1: Voluntary visually-guided eye movement task

All patients completed this task while being awake, unsedated, and comfortably seated on the bed in a dark room. Yet, complete darkness in the room was not feasible. A target circle with a diameter of 5 mm was binocularly presented on a 19-inch Acer V193 LCD monitor placed 60 cm in front of each patient (Refresh rate:75 Hz; Acer America, San Jose, CA, USA). Patients were instructed to visually follow a target intermittently and unpredictably moving from one place to another for 160 times in total (Video S1 on the website). A target pseudorandomly moved either to up-, down-, left- or right-ward direction (25% chance of each direction) with a distance of either 38 or 75 mm (50% chance of each distance) either in an instantaneous or smooth fashion (50% chance of each fashion). Instantaneous motions of a target were expected to elicit voluntary saccades of about 3.6° or 7.1°, whereas smooth motions of a target with a speed of 0.038 mm/msec (0.0036° per msec) were expected to elicit smooth pursuits. Each patient was instructed to fixate a still target during inter-motion intervals pseudorandomly ranging from 1,000 to 2,000 msec.

Task 2: Word reading task

Three patients (patients #2, 3 and 5) completed a word reading task (Wu et al., 2011) following the voluntary eye movement task. The main purpose of this experiment was to determine the spatio-temporal characteristics of intracranially-recorded gamma-oscillations modulated by the initially-detected involuntary saccade following presentation of a visual stimulus (Yuval-Greenberg et al., 2008). Patients were instructed to overtly read written words binocularly presented at the center of the monitor, in grayscale, on a black background, for 5,000 msec. Word stimuli consisted of 60 nouns (such as ‘dog’ and ‘banana’), of which size was 3 cm in height and ranged from 7 to 18 cm in width. A fixation cross was presented at the center of the monitor during inter-stimulus intervals pseudorandomly ranging 2,000 to 2,500 msec. The word reading sessions were recorded and the amplified audio waveform was integrated into the ECoG Recording System (Brown et al., 2008).

Measurement of ECoG amplitude modulations during the eye movement task

We determined ‘when’ and ‘where’ gamma-oscillations were modulated relative to the onset of target motion as well as that of eye movement. Each ECoG trial was transformed into the time-frequency domain using a complex demodulation technique (Papp and Ktonas, 1977) incorporated in BESA® EEG V.5.1.8 software (BESA GmbH, Gräfelfing, Germany; Hoechstetter et al., 2004). The time-frequency transform was obtained by multiplication of the time-domain signal with a complex exponential, followed by a low-pass filter. The low-pass filter used here was a finite impulse response filter of Gaussian shape, making the complex demodulation effectively equivalent to a Gabor transform. A given ECoG signal

was assigned a specific amplitude and phase as a function of frequency and time. Time-frequency transformation was performed for frequencies between 20 and 200 Hz, in steps of 10 Hz and 5 msec. At each time-frequency bin, we analyzed the percent change in amplitude relative to the mean amplitude during a 200-msec fixation period free of eye blinks (Figure S4 on the website). Such a change in amplitude is commonly termed "event-related synchronization and desynchronization" (Pfurtscheller and Lopes da Silva, 1999) or "temporal spectral evolution" (TSE) (Salmelin and Hari, 1994). In the present study, TSE values consisting of both phase-locked and non-phase-locked components (Tallon-Baudry and Bertrand, 1999) were used for further analysis.

To test for significance for each obtained TSE value, the following approach was employed using the BESA software. First, a studentized bootstrap statistics was applied to obtain an uncorrected p-value for each time-frequency bin. This test compared the amplitude in each time-frequency bin with that in the reference period. In a second step, correction for multiple testing developed by Simes (1986) was performed on these uncorrected p-values, since TSE values at neighboring time bins are partially dependent. For each channel and each frequency, p-values were sorted in ascending order (p_i, i = 1, …, N, where N is the number of time bins in a given frequency band). The maximum index m in the sorted array for which $p_i < \alpha*i/N$ was determined. All TSE values with i<m were considered statistically significant. The corrected significance level α was set to 0.05. In all figures, red color indicates augmentation of amplitude, and blue color attenuation of amplitude in the corresponding time-frequency bin relative to the reference period. Finally, an additional correction was employed (Wu et al., 2011). TSE values in a given electrode were declared to be significant only if a minimum of eight time-frequency bins in the gamma-band range were arranged in a continuous array spanning (i) at least 20-Hz in width and (ii) at least 20-msec in duration.

Localization of differential gamma-augmentation

We determined whether the degree of gamma-augmentation in a cortical site differed between saccade and pursuit trials. A given electrode site was declared to have significant gamma-oscillations preferentially augmented by a task, if TSE values differed between two tasks in a minimum of eight bins in the gamma-band range in a continuous array spanning at least 20-Hz in width and at least 20-msec in duration.

Measurement of ECoG amplitude modulations during the word reading task

We determined 'when' and 'where' gamma-oscillations were modulated relative to the onset of word presentation as well as that of initial involuntary saccade following word presentation. We specifically determined whether gamma-augmentations in occipital sites were better time-locked to the onset of word presentation or that of initial involuntary saccade following word presentation. The methodological details (such as the criteria defining a reference period) are described in the Supplementary Document on the website.

RESULTS

Behavioral data

The behavioral results are summarized in Table 2. The grand-mean response time across subjects was 209 msec (95%CI: 201 to 217 msec) in saccade trials and 299 msec (95%CI: 286 to 312 msec) in pursuit trials. The response time in saccade trials was shorter compared to that in pursuit trials.

The grand-mean latency between the onset of word presentation and the onset of initial involuntary saccade was 356 msec (95%CI: 319 to 392 msec); the grand-mean latency

between the onset of word presentation and the onset of patient's vocalization was 880 msec (95%CI: 813 to 946 msec).

Gamma-modulations elicited by instantaneous target motions and subsequent saccades

Gamma-augmentation initially involved the lateral, inferior and polar occipital regions following target motion, while gamma-augmentation in the medial occipital region mostly occurred around and after saccades (Videos S2 and S3 on the website). Both ECoG analyses relative to the onsets of target motion and saccades indicated that gamma-augmentation in the lateral occipital region occurred significantly earlier than that in the medial occipital region (see the quantitative data in Tables 3 and 4).

In patient #3, gamma-augmentation in the superior parietal lobule (consistent with the parietal eye field) and the Rolandic area reached significance after the onset of significant gamma-augmentation involving the occipital regions but before the onset of saccades, while gamma-augmentation in the premotor region (consistent with the frontal eye field) reached significance following the onset of saccades (Figure 1). In patient #2, gamma-augmentation in the premotor region also reached significance following the onset of saccades. In patient #1, gamma-augmentation in the posterior superior temporal-angular gyrus reached significance following the onset of saccades (Figure S5 on the website). The frequency band of gamma-augmentation generally ranged 50 to 180 Hz, with the most prominent augmentation commonly involving 80 to 150 Hz.

Gamma-augmentation in the anterior temporal region strictly time-locked to the onset of saccades

A total of five anterior temporal electrode sites in patient #3 showed transient gamma-augmentation strictly time-locked to the onset of saccades (Table 4). The peak of augmentation was exactly matched to the onset of saccades; the duration of significant gamma-augmentation ranged 30 msec on average (SD: 8 msec); the frequency band of amplitude-augmentation involved 40 to 120 Hz. The majority of such anterior temporal gamma-augmentations failed to be observed on bipolar montage using closest neighboring electrodes, whereas gamma-augmentations in the other regions were observed on both common average and bipolar montages (Figure 2). The spatio-temporal-spectral characteristics of anterior temporal gamma-augmentations are consistent with ocular and myogenic artifacts derived from eye movements (Yuval-Greenberg et al., 2008; Jerbi et al., 2009; Kovach et al., 2011).

Gamma-modulations elicited by smooth target motion and subsequent smooth pursuits

Time-frequency analysis of ECoG amplitude modulation during the pursuit trials suggested that gamma-augmentation involved the lateral, polar and inferior occipital regions somewhat earlier than the medial occipital regions, but group analysis failed to prove a significant difference in the onset latency across occipital sites. Compared to saccade trials, fewer sites showed significant gamma-augmentation (see the quantitative data in Tables S1 and S2 on the website).

Difference in gamma-modulations between saccade and pursuit trials

Significant difference in gamma-modulations between saccades and pursuits was noted in portions of occipital sites in all five patients (Figure 3). Time-frequency analysis relative to the onset of target motion demonstrated that 32 occipital sites (20 at medial, 4 at polar, 4 at lateral and 4 at inferior surface) showed larger gamma-augmentation in saccade trials compared to pursuit ones, whereas 4 occipital sites (3 at polar and 1 at lateral surface) showed larger gamma-augmentation in pursuit compared to saccade trials. Two occipital

sites (1 at medial and 1 at lateral surface) showed gamma-augmentation initially larger in saccade trials but subsequently larger in pursuit ones. One polar occipital site showed gamma-augmentation initially larger in pursuit trials but subsequently larger in saccade ones. Time-frequency analysis relative to the onset of eye movement yielded the observations similar to the above, although the number of sites showing significant gamma-augmentation was smaller.

Gamma-modulations elicited by perception of presented words as well as initial saccade following word presentation

Gamma-augmentation on the anterior medial surface of the occipital lobe was better time-locked to the onset of involuntary saccade occurring about 200–500 msec following word presentation rather than to the onset of word presentation in both patients #3 and #5 (Figure 4). The quantitative data are summarized in Table S3 and S4 on the website.

Ancillary results

We determined whether gamma-oscillations were modulated by involuntary eye blinks during fixation periods, and found that gamma-augmentation was elicited in two medial occipital sites following the onset of eye blink (Figure S6 on the website). We also found that saccades in a direction, compared to those in the opposite direction, elicited larger gamma-augmentation in some occipital sites in two patients (Figure S7 and S8 on the website).

DISCUSSION

Gamma-augmentation elicited by perception of target motion and subsequent eye movement

The novel observations in the present study are summarized in Table 5. Target motion elicited sustained gamma-augmentation involving the lateral, inferior and polar occipital regions, while subsequent saccades elicited sustained gamma-augmentation involving the medial occipital region. Gamma-augmentation in the lateral, inferior and polar occipital regions can be explained by increased attention to or analysis of a moving target (Figure S5 on the website; Tallon-Baudry et al., 2005), whereas gamma-augmentation in the medial occipital region may be elicited by the realigned images in the peripheral field (Wong and Sharpe, 1999; Yoshor et al., 2007).

The present study also showed that the degree of gamma-augmentation in the occipital regions was generally greater in saccade compared to pursuit trials, while the degree of gamma-augmentation in a portion of the polar occipital region was greater in pursuit compared to saccade trials. Larger degree of gamma-augmentation elicited by an instantaneous than gradual smooth motion of the target can be explained by greater attention to an instantaneous motion of the target compared to a gradual motion. Indeed, the response time was shorter on the saccade compared to the pursuit trials. Greater degree of gamma-augmentation elicited by a gradual target motion can be explained by finely tuned attention to the target's smooth motion occurring in the central vision (Stenbacka and Vanni, 2007).

The aforementioned occipital gamma-augmentation could not be explained by contaminations of ocular or myogenic artifacts. Occipital gamma-augmentation was sustained and not time-locked to the onset of saccades, whereas gamma-augmentation in anterior temporal regions lasting only 30 msec on average was strictly time-locked to the onset of saccades (Figure 2); thus, such anterior temporal gamma-augmentation was considered to be artifactual (Yuval-Greenberg et al., 2008; Ball et al., 2009; Jerbi et al., 2009). Furthermore, occipital gamma-augmentation was observed not only on common

average reference but also on bipolar montage using closest neighboring electrodes, whereas the majority of anterior temporal gamma-augmentations failed to be observed on bipolar montage, as previously reported (Kovach et al., 2011). Animation movies of event-related gamma-oscillations (Videos S1 and S2 on the website; Nariai et al., 2011) are difficult to create using ECoG measures on bipolar montage.

A subset of our patients showed gamma-augmentations involving the superior parietal lobule (BA 7; a portion of the parietal eye field) and the Rolandic region after the onset of gamma-augmentation in the lateral/inferior/polar occipital regions but before the onset of gamma-augmentation in the medial occipital region (Figure 1). On the other hand, gamma-augmentation involving the premotor region (BA 6; a portion of the frontal eye field) occurred following the onset of saccades. Our observations are consistent with previous fMRI studies showing that tasks involving saccades elicited cortical activation in the bilateral parietal and frontal eye fields (Grosbras et al., 2001; Merriam et al., 2001). Previous studies of monkeys using single neuron recording demonstrated that the spiking rates in parietal eye fields were increased before and at saccades (Lynch et al., 1977; Bruce and Goldberg, 1985). A study using simultaneous recording from both parietal and frontal eye fields showed that the spiking rates in the parietal eye fields were increased prior to those in the frontal eye fields when monkeys automatically attended a visually-salient object popping up on the screen (Buschman and Miller, 2007). Taking into account the timing, premotor gamma-augmentation might be related to the control rather than initiation of saccades. It has been known that the parietal eye field has a distinct output toward the frontal lobe (Cavada and Goldman-Rakic, 1989) in addition to that toward the superior colliculus (Lynch et al., 1985).

Gamma-augmentation elicited by word presentation and subsequent involuntary fixational saccades

The novel observations include that gamma-augmentation in the anterior medial occipital region was elicited by an involuntary saccade following word presentation rather than word presentation itself (Figure 4). This finding can be explained by the realigned images in the peripheral field following such a saccade (Wong and Sharpe, 1999; Yoshor et al., 2007). Otherwise, the word reading task elicited gamma-augmentation sequentially involving the widespread occipital region, left parietal, left prefrontal, left premotor and Rolandic regions, as described in previous ECoG studies (Lachaux et al., 2008; Vidal et al., 2010; Wu et al., 2011).

Methodological limitations

Inevitable limitations of ECoG recording include: sampling limitation, lingering effects of antiepileptic drugs, and inability to study healthy volunteers. Many of our patients had subdural electrodes placed only on the cortical surface of the presumed epileptogenic hemisphere; we were not able to evaluate the other hemisphere or subcortical structures. Since large bridging veins were present, we did not place large grid subdural electrodes but strip electrodes in some occipital regions. Antiepileptic drugs might have affected the findings of time-frequency ECoG analysis. Phenytoin was reported to elevate motor thresholds to transcranial magnetic stimulation but had no effect on motor-evoked potential amplitudes (Chen et al., 1997). A human study using macro-electrodes showed that reduction of antiepileptic drugs was followed by a 3% increase in duration of epileptogenic high-frequency oscillations at 80 Hz and above spontaneously arising from the seizure onset zone (Zijlmans et al., 2009).

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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- Eye movement tasks elicited augmentation of gamma-oscillations in the occipital lobe.
- Saccade and pursuit trials elicited differential gamma-augmentation.
- Saccades during word reading elicited gamma-augmentation in medial occipital sites.

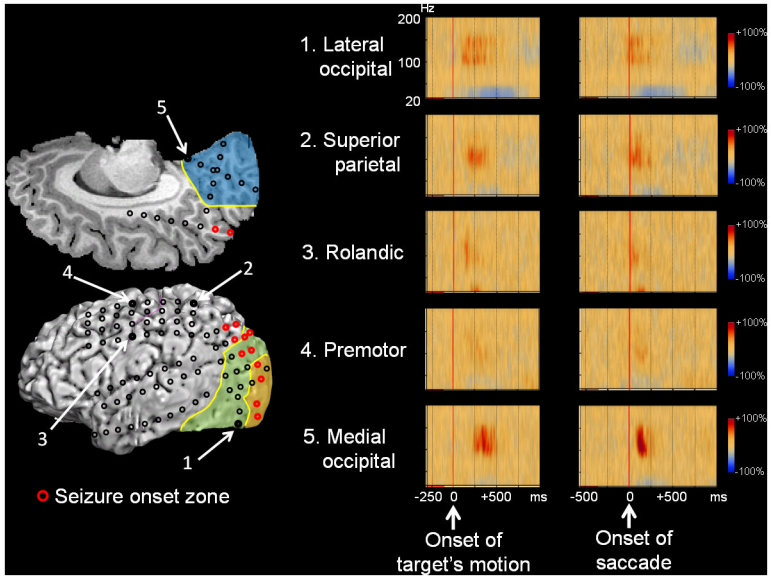

Figure 1. ECoG signals modulated during saccade trials in patient #3

Time-frequency analysis relative to the onset of target motion demonstrated that significant gamma-augmentation involving electrode #1 in the lateral occipital region at +105 msec, electrode #2 in the superior parietal lobule at +125 msec, electrode #3 in the Rolandic region at +125 msec, electrode #4 in the premotor region at +300 msec and electrode #5 in the medial occipital region at +225 msec. Time-frequency analysis relative to the onset of saccades demonstrated that significant gamma-augmentation involving electrode #1 in the lateral occipital region at −20 msec, electrode #2 in the superior parietal lobule at −35 msec, electrode #3 in the Rolandic region at +5 msec, and electrode #5 in the medial occipital region at +75 msec; thereby, gamma-augmentation at electrode #4 failed to reach significance. Taking into account the response time was 182 msec on average, gamma-augmentations in the lateral occipital region, superior parietal lobule and Rolandic region occurred prior to and during saccades, whereas those in the premotor and medial occipital regions occurred following the onset of saccade.

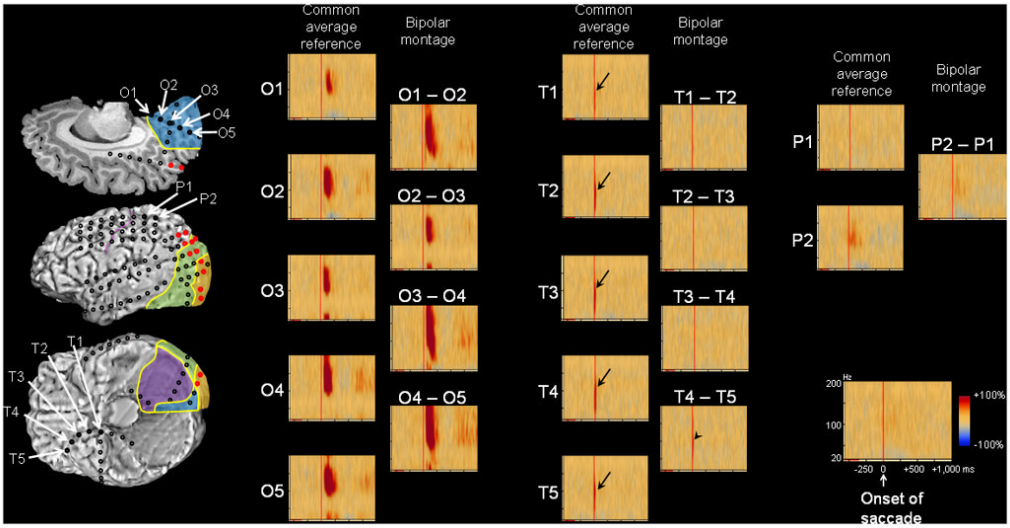

Figure 2. Transient gamma-augmentation of ocular origin in the anterior temporal region in patient #3

Time-frequency analysis relative to the onset of saccades demonstrated that gamma-augmentation strictly time-locked to the onset of saccades in the anterior temporal region (T1 through T5). Such gamma-augmentation of ocular origin was better noted on common average montage (black arrows), while significant gamma-augmentation of ocular origin failed to be seen on all bipolar derivations except at T4–T5 (black arrowhead). Gamma-augmentations in the occipital (O1 through O5) and parietal (P2) regions were noted on both montages.

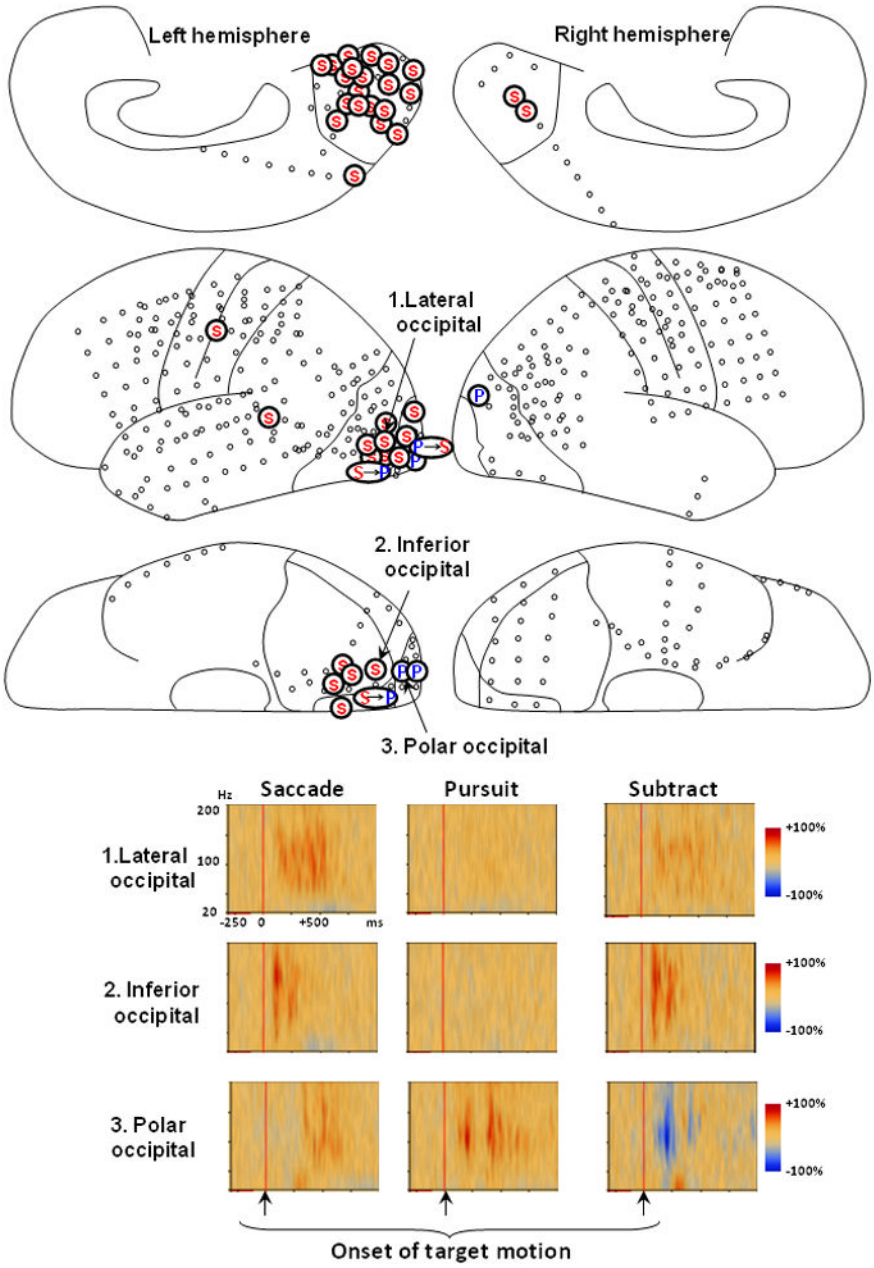

Figure 3. Difference in gamma-augmentation between saccade and pursuit trials

The overall results of time-frequency analysis comparing gamma-modulations between saccade and pursuit trials are shown. The locations of subdural electrodes in five patients were superimposed on a brain template. S: electrode sites showing larger gamma-augmentation in saccade trials compared to pursuit ones. P: electrode sites showing larger gamma-augmentation in pursuit compared to saccade trials. S→P: electrode sites showing gamma-augmentation initially larger in saccade trials but subsequently larger in pursuit trials. P→S: electrode site showing gamma-augmentation initially larger in pursuit trials but subsequently larger in saccade trials. Time-frequency matrixes below show that gamma-augmentation was preferentially elicited by saccade trials in lateral and inferior occipital

sites, while gamma-augmentation was preferentially elicited by pursuit trials in a polar occipital site.

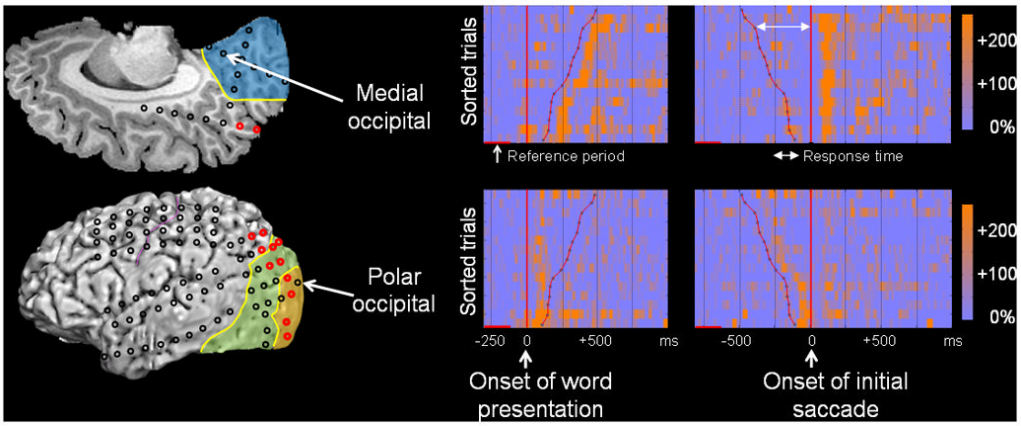

Figure 4. Gamma-augmentation elicited by initial involuntary saccades following word presentation

The temporal characteristics of gamma-range amplitudes are shown. The x-axis represents time, while the y-axis represents trials sorted according to the response time. Each row shows gamma-range amplitudes at 80–150 Hz averaged across three trials as a function of time. Gamma-augmentation in the polar occipital region was better time-locked to the onset of word presentation, whereas that in the medial occipital region was better time-locked to the onset of initial involuntary saccade following word presentation.

Table 1

Clinical profiles.

Patient	Gender	Age (years)	Hand dominance	Antiepileptic medications	Histology	VCI	PPVT4
1	Male	13	Right	OXC	Tumor in right parietal region	106	128
2	Female	15	Right	LEV	Tumor in left temporal region	N/A	91
3	Female	16	Right	OXC, LEV	Gliosis in left parietal-occipital region	121	91
4	Male	16	Right	OXC, LEV	Gliosis in right temporal region	87	84
5	Female	21	Right	LEV	Tumor in left occipital region	N/A	94

OXC: Oxcarbazepine. LEV: Levetiracetam. VCI: Verbal Comprehension Index. PPVT4: Peabody Picture Vocabulary Test—Fourth Edition.

Table 2

Behavioral results.

Patient	Onset latency of saccades		Onset latency of pursuits		Onset latency of initial involuntary saccades in the reading task		Onset latency of vocalizations in the reading task	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD
1	171	56	256	80	N/A	N/A	N/A	N/A
2	267	86	347	162	327	201	681	143
3	182	56	321	98	262	111	611	100
4	203	51	327	103	N/A	N/A	N/A	N/A
5	222	34	275	51	489	172	1262	476
								(msec)

The onsets of pursuits were significantly delayed compared to those of saccades. SD: standard deviation. N/A: not applicable. msec: milliseconds.

Table 3

Onset latency of gamma-augmentation relative to the onset of instantaneous target motion.

	Number of electrode sites showing significant augmentation (Number of patients showing significant augmentation)	Lower range of onset latency	Upper range of onset latency	Mean onset latency	95% CI lower	95% CI upper
Polar occipital	5 (2)	75	305	160	39	283
Lateral occipital	10 (4)	75	245	140	99	180
Inferior occipital	5 (2)	95	190	150	100	196
Medial occipital	25 (3)	80	480	230	189	271
Superior parietal	2 (1)	125	125	125	N/A	N/A
Premotor	2 (2)	300	315	310	N/A	N/A
Rolandic	1 (1)	125	125	125	N/A	N/A
Superior temporal/Angular gyrus	1 (1)	215	215	215	N/A	N/A
						(msec)

The onset of significant gamma-augmentation in the lateral occipital region was significantly earlier than that in the medial occipital region (see 95% confidence interval [95%CI]). N/A: not applicable. msec: milliseconds. Analysis was conducted on 18, 39, 27, and 42 electrodes on the polar, lateral, inferior and medial occipital regions.

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Table 4

Onset latency of gamma-augmentation relative to the onset of saccades.

	Number of sites showing significant augmentation (Number of patients showing significant augmentation)	Lower range of onset latency	Upper range of onset latency	Mean onset latency	95% CI lower	95% CI upper
Polar occipital	7 (2)	−25	115	75	31	110
Lateral occipital	8 (3)	−140	70	−50	−105	10
Inferior occipital	5 (2)	−115	125	−15	−149	119
Medial occipital	20 (3)	30	225	80	58	103
Superior parietal	1 (1)	−35	−35	−35	N/A	N/A
Rolandic	1 (1)	5	5	5	N/A	N/A
Superior temporal/Angular gyrus	1 (1)	50	50	50	N/A	N/A
Anterior temporal	5 (1)	−15	−5	−10	−16	−6
						(msec)

The onset of significant gamma-augmentation in the lateral occipital region was significantly earlier than those in the polar and medial occipital regions (see 95% confidence interval [95%CI]). N/A: not applicable. msec: milliseconds.

Table 5

Summary of the study.

	Hypotheses	Implications	Results
1	Target motion would elicit gamma-augmentation in lateral occipital region as well as parietal- (PEF) & frontal-eye fields (FEF).	Gamma-augmentation sequentially involved lateral occipital region, PEF and FEF. Gamma-augmentation in FEF occurred following the onset of saccade.	Lateral occipital gamma-augmentation may be related to increased attention to or analysis of target motion. Gamma-augmentation in FEF may be related to control rather than initiation of saccades.
2	Saccades would elicit gamma-augmentation in other occipital sites.	Gamma-augmentation involved medial occipital region following the onset of saccade.	Medial occipital gamma-augmentation may be elicited by realigned images in the peripheral field following saccades.
3	The degree of gamma-augmentation in occipital sites would differ between saccade and pursuit trials.	Except for a portion of the occipital pole, saccades elicited larger occipital gamma-augmentation compared to pursuits.	In functional studies comparing brain activation between two tasks, eye movement patterns during tasks may need to be considered as confounding factors.
4	Involuntary saccades following word presentation would elicit gamma-augmentation in anterior medial occipital region.	Gamma-augmentation in anterior medial occipital region was better time-locked to a saccade rather than word presentation.	Gamma-augmentation in anterior medial occipital region may be elicited by realigned images in the peripheral field following saccades.