Attention Modulates Gamma-band Oscillations Differently in the Human Lateral Occipital Cortex and Fusiform Gyrus

Catherine Tallon-Baudry[1,2], Olivier Bertrand[2], Marie-Anne Hénaff[2], Jean Isnard[3] and Catherine Fischer[3]

[1]LENA CNRS UPR 640, Hôpital de la Pitié-Salpétrière, 47 Bd de l'Hôpital, 75013 Paris, France, [2]INSERM U280, 151 cours Albert Thomas, 69003 Lyon, France and [3]Hôpital Neurologique, 59 Bd Pinel, 69003 Lyon, France

We studied the existence, localization and attentional modulation of gamma-band oscillatory activity (30–130 Hz) in the human intracranial region. Two areas known to play a key role in visual object processing: the lateral occipital (LO) cortex and the fusiform gyrus. These areas consistently displayed large gamma oscillations during visual stimulus encoding, while other extrastriate areas remained systematically silent, across 14 patients and 291 recording sites scattered throughout extrastriate visual cortex. The lateral extent of the responsive regions was small, in the range of 5 mm. Induced gamma oscillations and evoked potentials were not systematically co-localized. LO and the fusiform gyrus displayed markedly different patterns of attentional modulation. In the fusiform gyrus, attention enhanced stimulus-driven gamma oscillations. In LO, attention increased the baseline level of gamma oscillations during the expectation period preceding the stimulus. Subsequent gamma oscillations produced by attended stimuli were smaller than those produced by unattended, irrelevant stimuli. Attentional modulations of gamma oscillations in LO and the fusiform gyrus were thus very different, both in their time-course (preparatory period and/or stimulus processing) and direction of modulation (increase or decrease). Our results thus suggest that the functional role of gamma oscillations depends on the area in which they occur.

Keywords: attention, extrastriate cortex, intracranial EEG, synchrony, vision

Introduction

Oscillatory synchrony has been proposed as a mechanism of neural cooperativity enabling the dynamic formation of distributed cell assemblies (Singer and Gray, 1995). In humans, scalp electroencephalography (EEG) recordings consistently reveal the existence of synchronized oscillatory activity in the gamma range (> 30 Hz) when subjects experience a coherent visual percept (Muller *et al.*, 1996; Tallon-Baudry *et al.*, 1996; Revonsuo *et al.*, 1997; Tallon-Baudry *et al.*, 1997; Keil *et al.*, 1999; Rodriguez *et al.*, 1999; Grice *et al.*, 2001; Gruber *et al.*, 2002). A plausible interpretation of these findings is that objects giving rise to a coherent percept recruit visual areas that are synchronized in the gamma range. However, it is difficult to make inferences about the underlying cell assemblies from scalp recordings. We thus investigated the existence, localization and attentional modulation of gamma oscillations in a series of intracranial recordings in humans.

If gamma oscillatory synchrony were to play an important functional role, it should be confined to some discrete active regions rather than being ubiquitous in the brain, and this localization should be consistent from one subject to the other. Our first objective was thus to determine which regions were systematically engaged in oscillatory synchrony in all subjects and to check how these regions matched against the known functional anatomy of the human visual system.

Our second objective was to describe how these gamma oscillations were modulated by attention. Oscillatory synchrony could not only signal relatedness but could also act as a powerful attentional filter (Fries *et al.*, 2001b, 2002): synchronized outputs are likely to be more efficient on the target structure at the next processing stage than unsynchronized ones. Stimulus-driven gamma oscillations are indeed modulated by attention at the scalp level in humans (Gruber *et al.*, 1999; Shibata *et al.*, 1999). More generally, attention is known to modulate not only sensory responses, but also the activity preceding stimulus onset, when the subject 'prepares to attend' (Luck *et al.*, 1997; Kastner and Ungerleider, 2000). So-called 'baseline shifts' raise many questions (Driver and Frith, 2000; Driver and Frackowiak, 2001). In particular, how they might influence the following sensory response has not been much documented, although it is usually held they should convey some advantage to subsequent stimulus processing.

A series of 14 patients with depth electrodes implanted in extrastriate visual cortex were recorded in a blocked experimental design (Fig. 1). In the 'attend' condition, subjects prepared to attend while fixating a central cross (baseline) and actively processed the incoming stimulus for delayed comparison with a second stimulus. In the 'unattend' condition, subjects knew they had to detect a change in the luminance of the central fixation cross that could only occur at the end of the trial. No activity other than fixation was thus required during baseline in the 'unattend' condition, and the first stimulus was irrelevant. Subjects were reminded which task to perform at the beginning of each recording block. We present here how attention modulates both the gamma activity preceding stimulus onset and the gamma sensory response, in the lateral occipital cortex (LO) and the fusiform gyrus, two regions that play a key role in visual object processing as shown in numerous functional magnetic resonance imaging (fMRI) studies.

Material and Methods

Patients

Fourteen patients (6 males, 8 females; mean age 34, range 20–58 years) with medically intractable partial epilepsy were implanted with depth electrodes for presurgical seizure focus localization. Their visual acuities were normal or corrected to normal. One patient showed a scotoma that spared the central visual field. Recordings were performed at the end of the fortnight monitoring period, once a sufficient number of seizures had been recorded. At the time of recordings, most patients were under antiepileptic monotherapy, most often carbamazepine. Evoked potentials recording is part of the functional mapping of eloquent cortical areas that is performed routinely before epilepsy surgery in patients implanted with depth electrodes. According to the

French regulations concerning invasive investigations with a direct individual benefit, patients were fully informed about the electrode implantation, stereotactic EEG (SEEG) and evoked potential (EP) recordings, and the cortical stimulation procedures used to localize the epileptogenic and eloquent brain areas. All patients gave their informed consent to participate in the experiment.

Electrodes and Implantation Sites

Electrode contacts were 2 mm long and spaced every 3.5 mm (center-to-center). Depth probes (diameter 0.8 mm) with 10 or 15 contacts each were inserted perpendicularly to the midsagittal plane (Figs 2 and 3) using Talairach's stereotactic grid (Talairach and Tournoux, 1988). Electrode locations were measured on X-ray images obtained in the stereotactic frame. The depth of penetration of each contact was measured on the frontal X-ray image from the tip of the electrode to the midline, which was visualized angiographically by the sagittal sinus. The co-registration of the lateral X-ray image and a midsagittal MRI scan, both having the same scale of 1, gave the electrode coordinates in the individual Talaraich space defined by the median sagittal plane, the anterior commissure–posterior commissure(AC–PC) horizontal plane and the vertical AC frontal plane, these anatomical landmarks being identified on the three-dimensional MRI scans. Eventually, this procedure led to the superimposition of each electrode contact onto the patients' structural MRIs.The accuracy of the registration procedure was 2 mm, estimated on another patient's MR images obtained just after electrode explantation and in which electrode tracks were still visible. In order to pool results across subjects, these coordinates were normalized and projected onto the Talairach and Tournoux stereotactic atlas (Talairach and Tournoux, 1988). The analysis was restricted to the electrodes located within the visual extrastriate cortex but outside the epileptic focus. In particular, electrodes located in the anterior medial temporal structures and the hippocampus as well as electrodes located within lesions were excluded from the analysis.

Paradigm and Recordings

Patients were presented with two tasks in a blocked design (Fig. 1). In the first task ('attend' condition), they had to remember the first stimulus presented to decide whether it was identical or not to the second one. In the second task ('unattend' condition), they ignored the first stimulus but monitored a change in the color of the fixation point that could only occur at the end of the delay. Subjects were reminded at the beginning of each block of recordings which of the two tasks they were going to perform. Stimuli were smooth black shapes presented against a gray background. One trial consisted in a red fixation cross for 800 ms, first stimulus for 400 ms, delay for 800, 1200 or 1600 ms, and either second stimulus (attend condition) or red fixation cross (control condition) for 400 ms. Intertrial interval was randomized between 2500 and 3500 ms. Two or three 8 min blocks of 80 stimuli were recorded in each condition in each patient. Performance was monitored online and the difficulty of the task (difference between the two shapes or luminance decrement of the fixation cross) modified to keep the subject's performance 80-90% correct. The paradigm has already been presented in detail elsewhere (Tallon-Baudry *et al.*, 1998, 2001). In accordance with the online adaptation of task difficulty, all subjects performed both tasks 80-90% correct. Subjects performed slightly better but more slowly in the control than in the attend condition [mean performance: 84.8 ± 0.7% (control), 81.8 ± 1.2% (attend), paired *t*-test $P < 0.02$; mean reaction times from second stimulus onset: 1391 ± 10 ms (control), 1344 ± 15 ms (attend), paired *t*-test $P < 0.03$]. The video-display refresh rate was 60 or 100 Hz. Continuous data were acquired at a sampling rate of 1000 Hz with a 0.1–200 Hz bandwidth with a Neuroscan system. A vertical electro-oculogram was recorded to
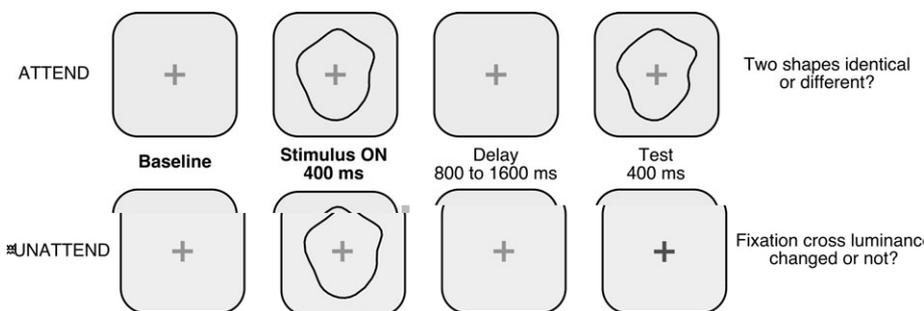
Figure 1. Paradigm. Two conditions were presented in a blocked design. In the 'attend' condition, subjects performed a delayed-matching to sample task. The first stimulus was thus attentively processed and actively encoded for comparison with the test stimulus after the delay. In the 'unattend' condition, the first stimulus was irrelevant: the subject had to monitor the color of the central fixation cross and report whether a color change occurred at the end of the delay. Data analysis focused on the effect of attention during baseline and stimulus encoding.
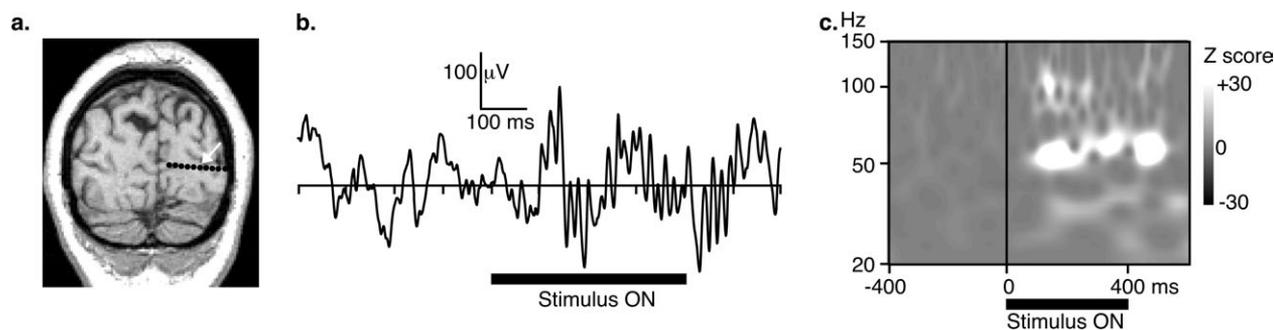
Figure 2. Large gamma oscillations from depth recordings in humans. (*a*) Depth multi-contact electrodes were inserted perpendicularly to the sagittal plane, at different locations in the visual extrastriate cortex. (*b*) Single trial at the electrode contact indicated by the arrow in (*a*). Large oscillations could be observed in raw data (0.1–200 Hz) at this recording site. (*c*) The power of these oscillations was quantified on a single trial basis in the time and frequency domain. Power was computed in the time (abscissa) and frequency (ordinate) domain and color-coded. Here, the light shade indicates a strong power at ~60 Hz, from 100 to 500 ms after stimulus onset. To study the reactivity of each region in response to the stimulus, we normalized the power in each frequency band with respect to pre-stimulus onset (Z score, no unit) for each single trial. Time–frequency plots of *Z*-scores were then averaged across single trials. This allows induced activity, i.e. activity appearing with a jitter in latency from one trial to the next, to be studied.
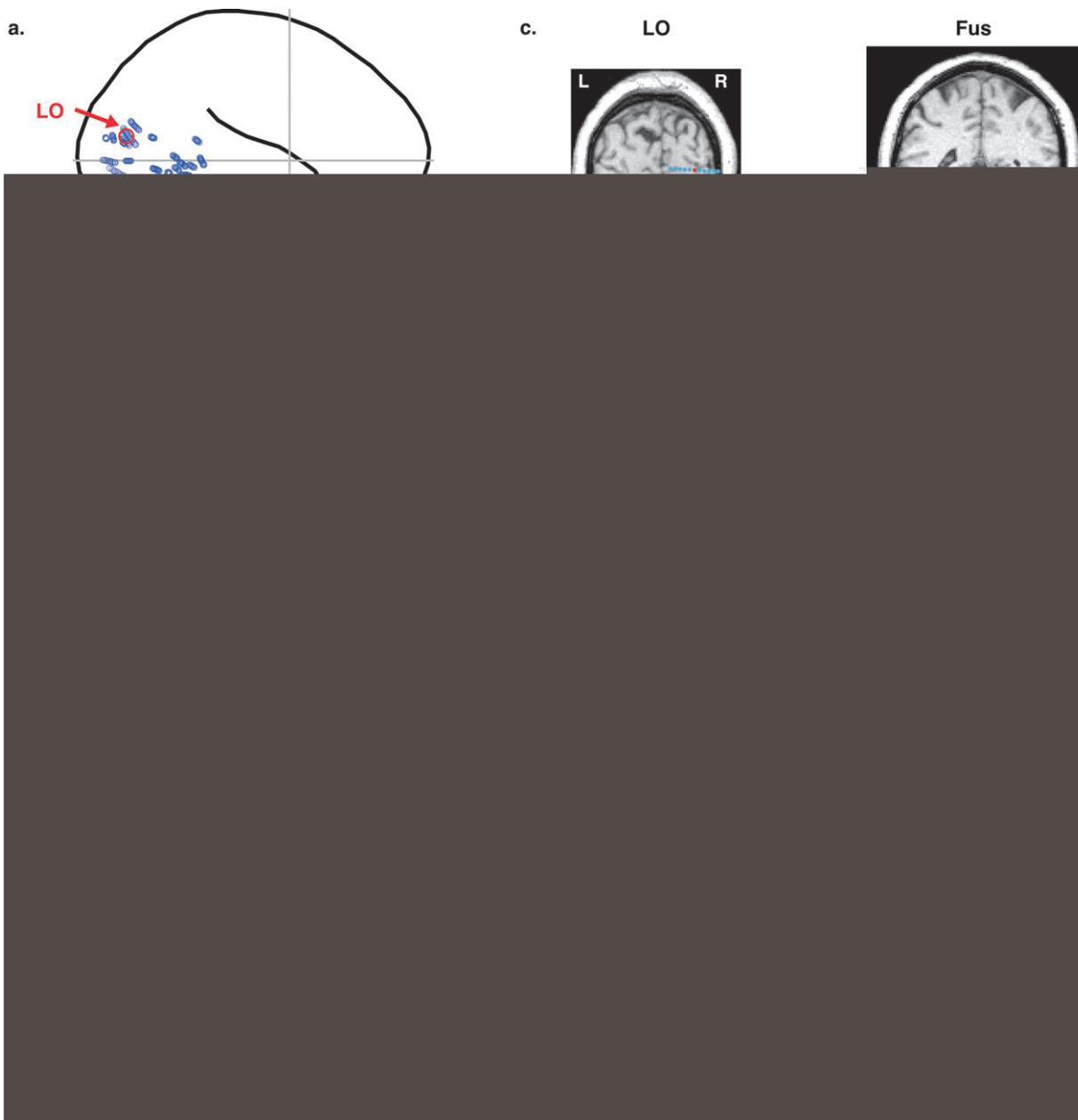
Figure 3. Localization of gamma oscillations. (*a*) Side-view rendering of the 291 implanted sites (blue circles) in the normalized Talairach space. The regions explored covered large parts of the ventral visual pathway. The two regions consistently showing large stimulus-induced oscillations are indicated by the red arrows (LO, lateral occipital region; Fus, fusiform gyrus). (*b*) Mean *Z*-score of the power of gamma oscillations at each recording sites, between 50 and 400 ms and 30 and 130 Hz. Because no differences between left and right hemispheres could be observed, all recording sites have been flipped to the right side of the brain for display purposes. Each electrode contact is represented by a circle whose color codes for gamma power. Responsive sites show up in yellow. Results are projected on three different horizontal slices, at +12, 0 and −12 mm. Responsive sites are gathered in LO and the fusiform gyrus (red rectangles at +12 and −12 mm). The only recording site showing gamma oscillations outside these two regions was a contact located in the posterior region of the calcarine sulcus (red arrow at +12 mm). (*c, d*) The anatomical location of the responsive sites was checked on individual MRIs. Two subjects that were simultaneously implanted in LO and the fusiform gyrus are presented. The most reactive contact is indicated in red on the MRIs and the corresponding time–frequency plot of the *Z*-score in the attend condition presented below. Note that the gamma oscillations occur simultaneously in the two areas at very different frequencies in the same subject. The best and worst gamma responses according to the criterion used to classify a site as responsive (mean *Z*-score > 2 for at least 200 ms in a 10 Hz frequency band between 30 and 130 Hz) are shown in *c*, left, and *d*, left, respectively.

monitor eye blinks and eye movements. The ground electrode could be either a contact in the bone or a scalp electrode placed on the forehead. The reference electrode was usually a contact in the skull. In some patients a deep electrode was used as a reference for recordings and the data were re-referenced offline prior to data analysis using a contact in the bone.

Data Analysis
Raw data were visually inspected and any trial containing an artefact (mainly eye blinks detected in the electro-oculogram) discarded, leaving

on average respectively 122 correct trials in the attend condition (range 86–169) and 117 correct trials in the control condition (range 88–158). There were not enough error trials to analyze these.

For each single trial, data were analyzed in the time–frequency domain by convolution with complex gaussian Morlet's wavelets with a ratio f/σ_f of 7, with f the central frequency of the wavelet and σ_f its standard deviation in frequency, the frequency ranging from 6 to 150 Hz in 2 Hz steps (Tallon-Baudry and Bertrand, 1999). This leads at 30 Hz to a wavelet with a σ_f of 4.28 Hz and a σ_t of 37.2 ms. At each

time t and frequency f the result of the convolution for trial j is a complex number:

$$P_j(t,f)e^{i\varphi_j(t,f)}$$

where p represents the power of the signal and φ its phase. To localize the electrode contacts showing gamma oscillations in response to the stimulus, a Z-score was computed at each time t and frequency f at each trial j:

$$Z_j(t,f) = (P_j(t,f) - \mu_j)/\sigma_j$$

where μ_j is the mean and σ_j the standard deviation of the baseline (–400 to –50 ms) power at frequency f for trial j (see Fig. 2 for an example on one trial). For a given single trial and at a given frequency, a Z-score of 2 indicates that the signal exceeds the baseline level by 2 standard deviations of the baseline level. Time–frequency plots of Z-score where then averaged across trials, enabling us to define the reactive frequency bands at each electrode contact (Fig. 3). This conservative procedure thus considers single trials independently. Because the intertrial variance is not taken into account, Z-scores are not enhanced by the fact that the same event occurs at each trial.

To quantify independently the attentional modulation of the baseline and of the sensory response, we worked directly on the mean value p of power in the 30–130 Hz frequency band. Statistical significance of attentional modulations were tested using randomization procedures on a subject-by-subject basis. These procedures have the great advantage that they can be applied to data of unknown distribution. Randomization procedures test whether a difference between two datasets (here attend and unattend) is or is not likely to have arisen by chance. The comparison between two groups involves randomly swapping data between groups and computing the difference for these resampled data. This procedure is repeated 1000 times per subject. If the original difference is larger than any of the 1000 differences obtained from the resampled data, then the original difference can be considered as significant with a P-value <0.001. The generalized Monte-Carlo test we used is fully described in Manly (1991). For comparison purposes, the same analysis has been replicated on the mean value p of power between 8 and 12 Hz (alpha range) and between 15 and 20 Hz (beta band) [The beta band has been shown previously (Tallon-Baudry *et al.*, 1998, 2001) to be reactive during the delay in the same paradigm].

Attentional modulations of the evoked potentials were analyzed in 50 ms time-window centered around the main peaks (see Results) on a subject-by-subject basis. The mean potential value in the 50 ms time-window (corrected by the mean amplitude in the –400 to 50 ms baseline) was measured for each single trial, in both conditions. For each subject, the attend and unattend conditions were compared using the Mann–Whitney U-test for unmatched samples.

Results

Existence and Localization of Gamma Oscillations
Large gamma oscillations could be observed at some recording sites on raw data during stimulus presentation (Fig. 2). These oscillations rose sharply between 100 and 150 ms, and were present during the whole stimulus presentation. Their latency varied from one trial to the other. Hence they tended to cancel out on the averaged evoked potential. To quantify these induced oscillations, time–frequency plots averaged across trials were computed for each recording site in the attend condition. The amplitude of the gamma response was defined as the mean between 50 and 400 ms and 30 and 130 Hz of the Z-transformed power. As a first approach, this amplitude was plotted at each implanted site in the Talairach normalized brain (291 contacts across 14 patients, Fig. 3a). Among the regions sampled, two regions consistently displayed a large gamma response. One region was located in the LO sulcus and the other in the fusiform gyrus (Fig. 3b). The only contact located in the vicinity of the calcarine sulcus (red arrow in Fig. 3b) also showed a gamma response (Fig. 4).
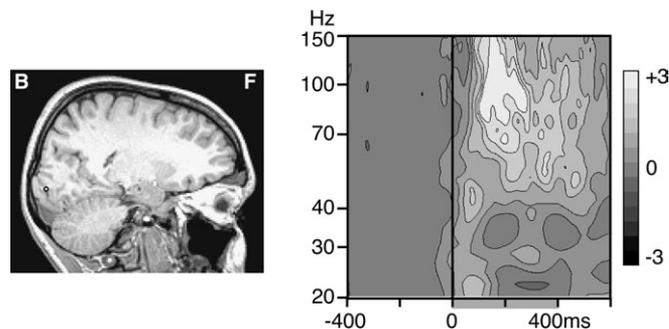
Figure 4. Gamma oscillations in the posterior calcarine region. A single contact in the vicinity of the calcarine sulcus (black circle on the MRI, left) displayed large gamma oscillations seen on the time-frequency plot of the mean Z-score (right). The peaking frequency of these oscillations was 74 Hz and their latency at half-height 152 ms. These values fall within the range observed in LO and the fusiform gyrus.

To quantitatively assess the localization of the gamma response, a site was defined as responsive if it displayed gamma oscillations whose mean Z-score exceeded 2 for at least 200 ms during stimulus presentation in a 10 Hz frequency band located between 30 and 130 Hz. Going back to individual structural MR images, we checked that all patients implanted with an electrode in the fusiform gyrus displayed a gamma response to the stimulus (5 patients, mean Talairach coordinates in mm $x = 31$, $y = -53$ and $z = -11$) and that all the patients implanted with an electrode in the LO region displayed a gamma response to the stimulus (4 patients, mean Talairach coordinates in mm $x = 24$, $y = -80$, $z = 11$). Figure 3 illustrates the full amplitude range of the sites considered responsive, Figure 3c (left) showing the largest gamma response and Figure 3d (left) the weakest.

Gamma oscillations were confined within these structures: contacts located a few millimeters away did not show any oscillatory response. Figure 5 illustrates the spatial distribution of gamma oscillations along four electrode tracks recorded in a single patient. The lateral extent of the gamma response is small, in the range of 5 mm. None of the other implanted regions showed large gamma oscillations during stimulus encoding (Fig. 3a,b) according to the criterion defined above, except for the single electrode contact located in the posterior part of the calcarine sulcus (Fig. 4).

Time and Frequency Characteristics of Gamma Oscillations
Oscillations rose between 100 and 160 ms at all sites, with a latency at half height of 138.0 ± 10.2 ms (mean ± SEM) in LO and 117.6 ± 15.7 ms in the fusiform gyrus. Across all patients, the difference in latency between the two regions was not significant (Mann–Whitney U-test, $P = 0.54$). Two patients were simultaneously implanted in LO and the fusiform gyrus. These two patients showed opposite trends, one showing a shorter latency in LO and the other a shorter latency in the fusiform gyrus. The latency difference between LO and the fusiform gyrus remained small in these two patients (22 ms in one patient, 45 in the other). There was thus no evidence for one site responding systematically before the other, either in the two cases of simultaneous recordings in LO and the fusiform gyrus or across the group of patients.

The peaking frequency of gamma oscillations varied a lot from one patient to the other and one site to the other, ranging from 32 up to 120 Hz. The frequencies in LO and the fusiform
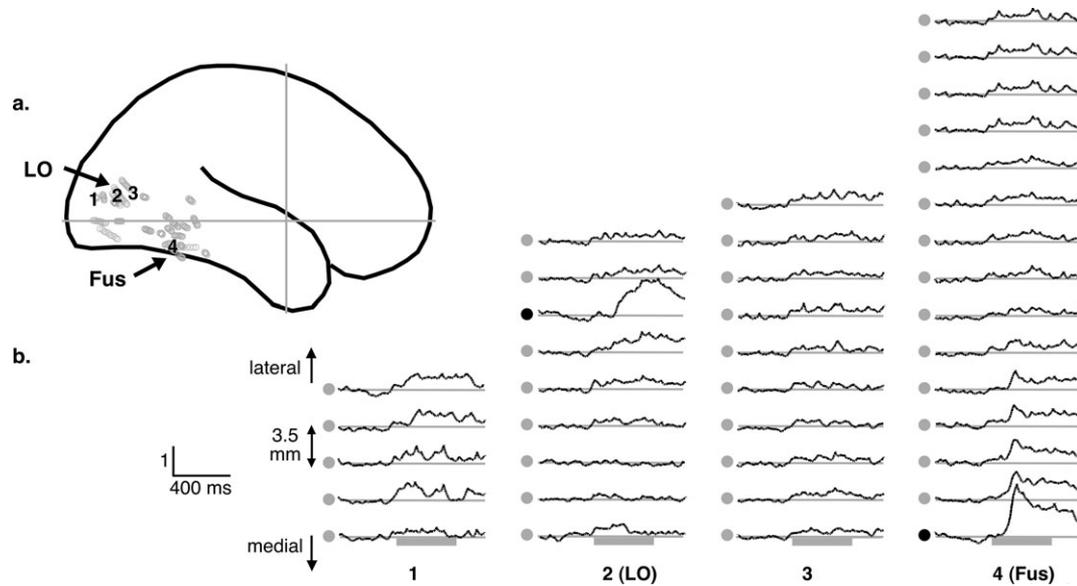
Figure 5. Spatial distribution of gamma responses: example along four electrode tracks in one subject. (*a*) Localization of the four electrode tracks in the extrastriate visual cortex of a single patient. Tracks number 2 and 4 explore the LO region and the fusiform gyrus respectively. (*b*) Time-course of the 30–130 Hz *Z*-transformed power at each recording sites along the four tracks. The two responsive contacts are indicated by black dots. Adjacent contacts (distance between contacts = 3.5 mm) were only weakly responsive, suggesting that the region generating the gamma oscillations has a limited spatial extent, in the range of 5 mm.

gyrus were markedly different in the same patient (Fig. 3*c,d*) in the two cases of simultaneous implantation. However, there did not seem to be any systematic difference in frequency between LO and the fusiform gyrus: one patient showed a higher frequency in LO than in the fusiform gyrus, the other a lower frequency in LO than in the fusiform gyrus. Across all patients, there was no significant difference in frequency between LO (84.5 ± 14.7 Hz, mean ± SEM) and the fusiform gyrus (62.5 ± 7.9 Hz) (Mann–Whitney *U*-test, $P = 0.54$).

Attentional Modulation of Gamma Oscillations

Since attention could modulate independently the amplitude of gamma oscillations both before and after stimulus onset, attentional modulations were analyzed directly on power measure rather than on *Z*-scores. The power of gamma oscillations in the 30–130 Hz range was compared in the attend and unattend conditions in the two regions of interest, LO and the fusiform gyrus. Two time-windows were defined, one during the baseline (–400 to –50 ms, before stimulus onset), when the subject prepared to attend, and one during stimulus presentation (50–400 ms after stimulus onset), when the subject processed the stimulus. Differences in gamma power between the attend and unattend conditions were tested on a subject-by-subject basis using Monte-Carlo randomization procedures.

During baseline, attention did not modify the amplitude of gamma oscillations in the fusiform gyrus ($P > 0.15$ at each of the five recording sites) but increased significantly the baseline gamma power in LO ($P < 0.03$ at each of the four recording sites). During stimulus encoding, attention increased the gamma response in the fusiform gyrus ($P < 0.03$ in the five patients) but decreased the gamma response in LO ($P < 0.02$ at the four sites). Attentional modulations of gamma power are summarized in Figure 6: in the fusiform region, attention did not modify the baseline level of gamma oscillations but increased the oscillatory response to the stimulus. In LO, the baseline level of gamma oscillations was enhanced by attention, but
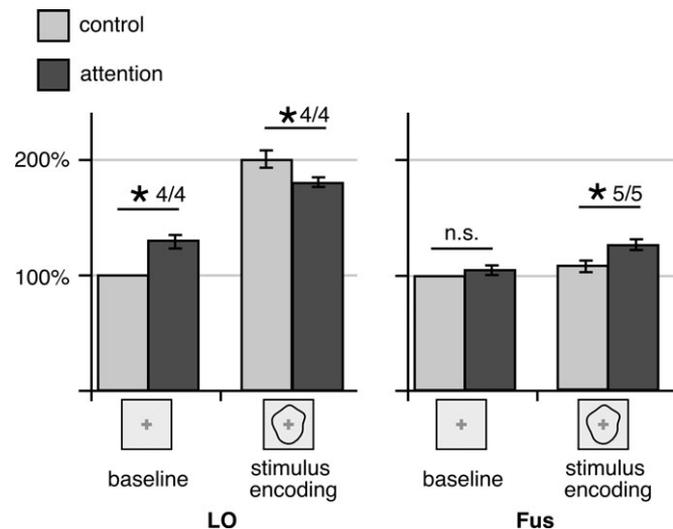
Figure 6. Attentional modulation of gamma oscillations in LO (left) and in the fusiform gyrus (right), during baseline and stimulus encoding. Because attention could modulate the baseline level and stimulus-induced gamma oscillations independently, attentional modulations were analyzed on power measures, not on *Z*-scores. The power of gamma oscillations was normalized, 100% corresponding the amount of gamma oscillations during the baseline in the unattend condition in each subject. Error bars represent the standard error of the mean. In the attend condition, gamma power during baseline was enhanced in LO, and this was followed by a sensory response smaller than in the unattend condition. These two effects were significant in the four subjects implanted in LO (Monte-Carlo procedures). In the fusiform gyrus, attention did not modulate the baseline but significantly increased the stimulus-induced gamma oscillations in the five subjects implanted in this area.

the following oscillatory response to the stimulus was reduced. These amplitude modulations were not accompanied by a modification of the peaking frequency of the oscillations (Wilcoxon test for matched pairs, $P = 0.55$), or by a change in the latency of the stimulus-induced oscillations (latency at half width, Wilcoxon test for matched pairs, $P = 0.28$).

The attentional modulation of oscillations was confined to the gamma range. No consistent attentional modulation of the baseline level or of the stimulus response could be observed, either in the alpha range (8-12 Hz) or in the beta range (15–20 Hz). In the alpha range, the stimulus-induced power was not modulated by attention, either in LO ($P > 0.1$ at each site) or in the fusiform gyrus ($p > 0.2$ at each site). During baseline, there was no modulation of alpha power by attention in the fusiform gyrus ($P > 0.11$ at each site). In LO, only one recording site out of four showed a significant increase of alpha oscillations in the baseline in the attend condition ($P < 0.01$ at one site). In the beta band (15–20 Hz), two recording sites (one in the fusiform gyrus and the other in LO) showed the same modulations by attention than in the gamma range. These two sites were those showing the lowest peaking frequency of gamma oscillations (32 and 48 Hz respectively). The effects obtained in the 15–20 Hz range at these two sites are thus likely to correspond to the spreading of a phenomenon centered at higher frequencies.

One electrode contact was located in the posterior part of the calcarine sulcus (Fig. 3b, arrow) and showed large gamma oscillations in response to the stimulus onset. At this site, attentional modulations were qualitatively similar to those observed in the fusiform gyrus: the baseline level of gamma oscillations was not modulated by attention ($P = 0.3$), and there was a trend for the stimulus-induced oscillatory response to be enhanced ($P = 0.07$).

Evoked Potentials in LO and the Fusiform Gyrus

In LO, evoked potentials with large peaks could be identified in two out of four patients. They were similar to the evoked potentials described in the literature (Allison *et al.*, 1999; Huettel *et al.*, 2004), with a first deflection around 140 ms, a second one around 200 ms and a third one at 290 ms. In the two other patients evoked potentials were small and did not show any prominent deflections. Figure 7a illustrates the worst (top) and best (bottom) evoked responses recorded in LO. To quantify attentional modulations in each patient, the amplitude of the response was averaged in a 50 ms window centered around 290 ms on each single trial, in the attend and unattend condition. In three out of four patients, the amplitude of the evoked response around 290 ms was modulated by attention, with more positive values in the attend condition (Mann–Whitney U-test on single trials, $P < 0.03$ in three patients, $P = 0.23$ in the remaining patient).

Evoked potentials recorded in the fusiform gyrus were also consistent with the literature (Huettel *et al.*, 2004), with a first deflection around 100 ms and a second peak around 180 ms. None of these two peaks were modulated by attention (Mann–Whitney U-test, $P > 0.37$ in the five patients). The third peak around 300 ms was modulated by attention in four out of five patients ($P < 0.05$). Suprisingly, this modulation could be either positive or negative, depending on the subject, as illustrated in Figure 7b. No polarity inversion along the electrode track could be observed in any patients, either at 290 ms or earlier.

Gamma Oscillations and Evoked Potentials

Oscillatory induced gamma responses and evoked potentials were not systematically co-localized. Large evoked potentials could be observed outside LO and the fusiform gyrus at various extrastriate recording sites not displaying any gamma activity. Conversely, evoked potentials were not always present in LO and the fusiform gyrus, where large gamma oscillations
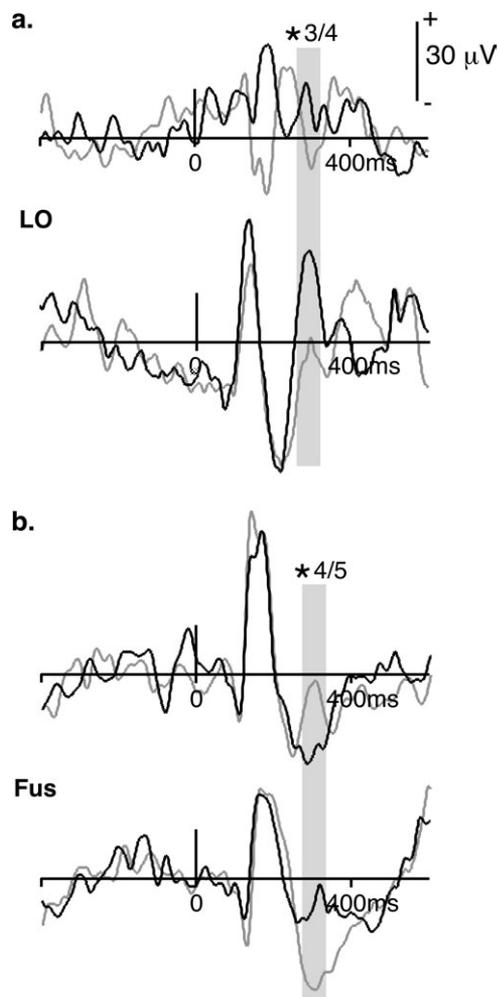

Figure 7. Evoked potentials in the attend (black lines) and unattend (gray lines) conditions. (*a*) In LO, the evoked response was barely visible in two patients (top, example of a weak response) or presented prominent peaks (bottom, example of a well-defined evoked potential). The mean amplitude around the third peak at 290 ms was significantly modulated by attention in three out of four patients (gray shading) with more positive values in the attend condition. (*b*) In the fusiform gyrus, evoked potentials showed peaks at 100, 180 and 300 ms. The third component at 300 ms was significantly modulated by attention in four out of five patients (gray shading), but the direction of modulation was not consistent across patients (more positive or more negative values in the attend condition, depending on the subject).

were observed. Figure 8 shows an example of a recording site in LO showing a large oscillatory-induced response but barely an evoked response, and an example in the lingual gyrus where a large evoked potential could be recorded without concomitant gamma oscillations. Across all sites defined as responsive in the gamma range, the correlation between the evoked potential (mean area under the curve) and the induced gamma response (mean Z score) between 50 and 400 ms is low and not significant (Spearmann correlation coefficient $\rho = 0.144$; $P = 0.5765$).

Discussion

We report the existence of sustained gamma oscillations in the human lateral occipital sulcus (four cases), the fusiform gyrus (five cases), as well as in the posterior calcarine region (one case). These oscillations were characterized by their high central frequency (from 32 up to 120 Hz) and their sustained
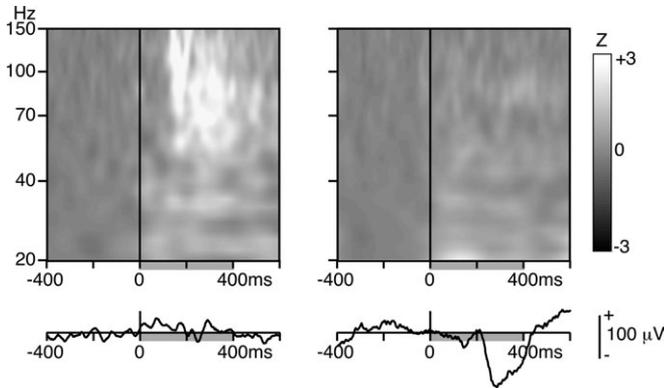
Figure 8. Gamma oscillations and evoked potentials are not systematically colocalized. Large gamma oscillations could be observed at recording sites not displaying a clear evoked response (left, activity in LO). Conversely, large evoked responses could be obtained without concomitant gamma oscillations (right, activity in the lingual gyrus).

time-course (plateau maintained throughout stimulus presentation). Sustained gamma oscillations in response to simple visual stimulus have already been observed in the calcarine sulcus in one epileptic patient (Chatrian *et al.*, 1960) as well as in the monkey lunate gyrus (Hughes, 1964; Rols *et al.*, 2001). More transient and broad-band modulations have been reported in the human temporal lobe (Klopp *et al.*, 1999; Lachaux *et al.*, 1999). The high frequency and sustained time-course of those intracranially recorded gamma oscillations are in contrast to the lower frequency (~30 Hz) and transient increase of gamma oscillations observed with occipital scalp EEG electrodes in the same paradigm (Tallon-Baudry *et al.*, 1998). This suggests that either only the lower components of gamma oscillations can be observed at the scalp level, or that the brief burst of oscillatory activity detected at scalp occipital electrodes reflects complex and transient interactions between sustained oscillations occurring at different frequencies in the LO sulcus and fusiform gyrus. The third possibility is that the signal at occipital scalp electrodes is dominated by another source of more transient gamma oscillations that was not investigated here, given the necessarily finite sampling of the occipito-temporal lobe obtained here.

The two active regions (LO sulcus and fusiform gyrus) were anatomically well localized. All contacts in the posterior fusiform gyrus displayed large oscillations, while the power of these oscillations dropped close to zero as soon as the contacts were localized either more laterally or just above the fusiform gyrus. The LO region is more complex anatomically (Duvernoy, 1999). In some patients the LO sulcus itself could be identified without any doubt, in others the responsive contacts could be rather located in the transverse occipital sulcus. In any case the lateral extent of the gamma responsive region was again confined to a few contacts.

Although the electrode distribution covers pretty well the posterior ventral visual pathway, it cannot be excluded that an active region has not been investigated. For instance, only one electrode track explores the calcarine sulcus. It is all the more possible that an active region has not been sampled since the spatial extent of gamma oscillations is small, of the order of 5 mm. However, it is interesting to note that the two regions we identified on the basis of the strength of their gamma oscillatory response have repeatedly been reported as activated in object

perception tasks in fMRI experiments. The lateral occipital complex is a region that was originally functionally defined as responding more to objects than to their scrambled counterpart (Malach *et al.*, 1995; Grill-Spector *et al.*, 1998b). It was also shown to be strongly involved in object shape analysis (Grill-Spector *et al.*, 1998a; Kourtzi and Kanwisher, 2001). This vast complex was subdivided in a dorsal region referred to as LO and a more anterior and ventral region in the posterior fusiform gyrus called pFs (Grill-Spector *et al.*, 1999; Malach *et al.*, 2002). The anatomical localization of the two foci showing large gamma oscillations during stimulus presentation fits quite well with LO and pFs as defined by fMRI experiments. The differences in frequency and the different effects of attention in LO and the fusiform gyrus further support the idea that they are two functionally distinct regions (Grill-Spector *et al.*, 1999; Malach *et al.*, 2002).

Stimulus-induced gamma oscillations (appearing with a jitter in latency from one trial to the other) and stimulus-locked evoked potentials (appearing with a fixed delay after stimulus onset) were not systematically colocalized: large oscillatory responses could be observed in the absence of evoked potentials and vice versa. The observation of gamma oscillations without concomitant evoked potentials points to the relevance of both types of activity when deciding whether or not an area is functional prior to a surgical ablation in clinical practice. It also suggests that gamma oscillations are worth taking into account when attempting to combine electrophysiological and fMRI data. Indeed, the spatial correlation between evoked potentials and BOLD responses has been found to be weak, especially in the fusiform region (Huettel *et al.*, 2004), while the BOLD signal seems to correlate well with the plateau of 40–130 Hz oscillations in local field potentials in monkeys (Logothetis *et al.*, 2001; Logothetis, 2003).

The gamma responses in LO and the fusiform gyrus were modulated by attention. Oscillatory synchrony has been proposed to be a mechanism of attentional selection (Fries *et al.*, 2001b, 2002), the rationale being that coincident spikes are more likely to be efficient on subsequent processing stages. The increase of gamma oscillations by attention we observe in the fusiform gyrus fits well with this interpretation. It is also in keeping with fMRI studies showing that attention enhances activity in this region (Wojciulik *et al.*, 1998; Vuilleumier *et al.*, 2001; Pessoa *et al.*, 2002). Whether the enhancement of the sensory gamma response we observe in the posterior fusiform region relates to the enhancement of gamma activity by spatially selective attention described in monkey area V4 (Fries *et al.*, 2001b) is not clear, and the homology between human LO / pFs and monkey areas V4 / TEO remains a matter of intense debate (Tootell and Hadjikhani, 2001; Zeki, 2003; Denys *et al.*, 2004).

In LO, the pattern of attentional modulation was very different and more complex than in the fusiform region. Because of these differences between LO and the fusiform gyrus, it seems unlikely that our results can be explained either by a global effect of the medical treatment some of the patients received or by a global state change between conditions. In LO, attention increased the baseline level of gamma oscillations: when preparing to attend the shape, LO was more synchronized in the gamma range. It should be noted that the fixed duration of the baseline probably enhanced attentionally driven anticipatory changes in neural dynamics. So-called 'baseline-shifts' are usually thought to convey an advantage to the attended stimulus — this advantage being most often considered to be an

increase in the sensory response. This appealing notion is only partly supported by experimental evidence. Some studies indeed reported an increase of the sensory response following baseline enhancement in human area MT (Chawla *et al.*, 1999), V2 and V4 (Kastner *et al.*, 1999), as well as an increase in baseline gamma activity followed by a large gamma response in monkey area V4 (Fries *et al.*, 2001b). However, others studies found that an increase of activity during baseline led to either no modification of the sensory response in human area V1 (Kastner *et al.*, 1999) or even to a decreased response in monkey areas V2 and V4 (Luck *et al.*, 1997).

In our findings, the increase in gamma oscillations during baseline was followed by a reduced gamma response to the stimulus in the attend condition. How can this reduced response facilitate stimulus processing? A decisive advantage that could be given to the attended stimulus is the speeding of its processing. The increase in pre-stimulus oscillatory synchrony by attention in LO could lead to a better temporal coordination of the first spikes following stimulus onset, thereby increasing the efficacy of neural firing on subsequent processing stages (Fries *et al.*, 2001a). In the attend condition, the temporal coordination of membrane potential fluctuations in LO during the expectation period could enable a brief but efficient burst of spikes in response to the stimulus. Processed information would then quickly be transmitted to other areas such as the fusiform region in which the processing of the attended shape is large and sustained when paying attention to the stimulus. The hypothesis that the strength of oscillatory synchrony in LO influences the latency of the spiking output thus cannot be readily tested in the experiment presented here, because the electrodes we used record local field potentials, considered to reflect mainly intra-cortical processing, but not the spiking activity related to the output of the structure (Logothetis, 1998).

In the unattend condition, the stimulus is irrelevant but produces large gamma oscillations in LO. It should be noted that the perceptual load of the task in the unattend condition (detection of a luminance change of the fixation cross at the end of the delay) is low at the time of stimulus onset. As postulated by Lavie (1995) and shown by Rees *et al.* (1997), irrelevant stimuli are automatically processed when the concurrent task does not exhaust perceptual capacities. It could thus be that in the unattend condition the irrelevant stimulus is fully processed in LO, yielding large gamma oscillations, but that information is not transmitted to the fusiform gyrus which remains silent in the unattend condition.

Our results demonstrate the existence of a functional dissociation between gamma oscillations occurring simultaneously in two distinct extrastriate regions. Gamma oscillations were observed to occur at markedly different frequencies in LO and the fusiform gyrus during stimulus encoding (Fig. 3*c,d*). A similar difference in the central frequency of stimulus-related oscillatory activity was already reported from the anesthetized monkey areas V1 and V4 (Rols *et al.*, 2001). This could suggest that oscillations during stimulus encoding reflect local, within-area processing rather than a synchronized assembly distributed over distinct functional areas. The different attentional modulation of gamma oscillations in LO and the fusiform gyrus supports the idea that gamma oscillatory synchrony could play a different role depending on the functional specificity of the area in which the oscillations occur. Self-generated preparatory attention influenced the baseline level of gamma oscillations in LO, while stimulus-driven oscillations were modulated by

attention in opposite directions in LO and the fusiform gyrus. Attention thus seems to influence neural synchrony differently at different levels of processing. Internally driven and stimulus-driven attention may either interact as in LO, or act separately as in the fusiform gyrus. Attentional mechanisms seem finely tuned both in time, depending on whether the subject prepares to attend or actually pays attention to the stimulus, and in space, depending on the functional specificity of the area considered. Our study thus reveals a pattern of attentional modulations more complex than originally thought. However, this complexity potentially enhances the capacity of the system by increasing its flexibility and thereby its ability to provide an adapted response in different attentional conditions.

Notes

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