

EEG and MEG: Relevance to Neuroscience

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To understand dynamic cognitive processes, the high time resolution of EEG/MEG is invaluable. EEG/MEG signals can play an important role in providing measures of functional and effective connectivity in the brain. After a brief description of the foundations and basic methodological aspects of EEG/MEG signals, the relevance of the signals to obtain novel insights into the neuronal mechanisms underlying cognitive processes is surveyed, with emphasis on neuronal oscillations (ultra-slow, theta, alpha, beta, gamma, and HFOs) and combinations of oscillations. Three main functional roles of brain oscillations are put in evidence: (1) coding specific information, (2) setting and modulating brain attentional states, and (3) assuring the communication between neuronal populations such that specific dynamic workspaces may be created. The latter form the material core of cognitive functions.

1. Introduction

The EEG, i.e., the electroencephalogram, is the record of brain electrical fields (Berger, 1929), while the MEG, i.e., the magnetoencephalogram (Cohen, 1972), is the record of brain magnetic fields. Berger's driving force in his search of brain electrical activity "was the quest for the nature of the all-powerful force of mental energy (Psychische Energie)" (Niedermeyer and Schomer, 2011). The EEG and MEG are very close methodologies, since the main sources of both kinds of signals are essentially the same, i.e., ionic currents generated by biochemical processes at the cellular level.

Traditionally, EEG/MEG signals are described in terms of frequency bands, the limits of which were artificially defined without knowledge of neurophysiological mechanisms. Nonetheless, statistical factor analysis of EEG spectral values (Lopes da Silva, 2011b) yield clusters of frequency components that show considerable overlap with the frequency bands classically accepted, namely infraslow (<0.2 Hz), δ (from 0.2 to 3.5 Hz), θ (from 4 to 7.5 Hz), α and μ (from 8 to 13 Hz; see also 5.2.2.), β (from 14 to 30 Hz), γ (from 30 to 90 Hz), and high-frequency oscillations (HFO; >90 Hz). The term "oscillation" applied to EEG/MEG signals is sometimes used in a rather loose way. EEG/MEG activity within a given frequency range does not imply that a well-defined oscillation exists; in order to identify an EEG/MEG oscillation, one has to show that there is a spectral peak within the frequency band of interest. The oscillation is then defined by the peak frequency, bandwidth, and power (or amplitude).

Many EEG/MEG studies in the field of neurocognition concern time-locked-evoked or event-related potentials (ERPs) or magnetic fields (ERFs), which have been the object of many overviews (cf. Schomer and Lopes da Silva, 2011) and are not explicitly surveyed here. In the last decades, investigations of ongoing EEG/MEG signals, particularly neuronal oscillations, in association with cognitive events have gained a noteworthy place. These activities are induced by cognitive events but are not precisely time locked with such events. In this Primer, we concentrate on these EEG/MEG-induced activities in which oscillations occupy a prominent place.

Some scientists have expressed skepticism about the value of brain oscillations and EEG/MEG rhythmic activities in advancing the understanding of brain processes underlying cognitive functions. For instance, in their review on "Network Oscillations," Sejnowski and Paulsen (2006) state that notwithstanding "extensive work on the behavioral and physiological correlates of brain rhythms, it is still unresolved whether they have any important function in the mammalian cerebral cortex." Not so long ago, it was not uncommon to find the epithet "epiphenomena" applied to brain oscillations. Here we present and discuss experimental evidence that supports the contention that EEG/MEG signals, notably certain neuronal oscillations, or combinations of neuronal oscillations, are well-defined neurophysiological mechanisms that are relevant to understand how cognitive processes emerge.

In this Primer, we stress that human EEG/MEG signals should be seen as strongly linked to basic animal brain physiology; the animal studies have the advantage of allowing detailed neurophysiological investigations at the micro- and mesoscopic levels, but human studies have the advantage of enabling studies of brain signals in direct relation with complex cognitive paradigms. Animal and human studies concerning the dynamics of brain signals should be seen as complementary.

This Primer is not a review but just an introduction to the theme "what can EEG/MEG signals tell us about the brain," illustrated by some relevant examples from the literature.

2. EEG and MEG: A Bit of Biophysics and Neurophysiology

2.1. How Can Neuronal Electric/Magnetic Fields Be Picked Up at a Distance?

One condition is that an assembly of neurons should form a functional entity. This means that a population of neurons of sufficient size should be active in a coordinated way in time and spatially organized, such that their electric and magnetic fields may be recordable at a distance. This is the case of pyramidal neurons of the cortex that are arranged in the form of a palisade, with the main axes of their dendritic trees parallel to each other and

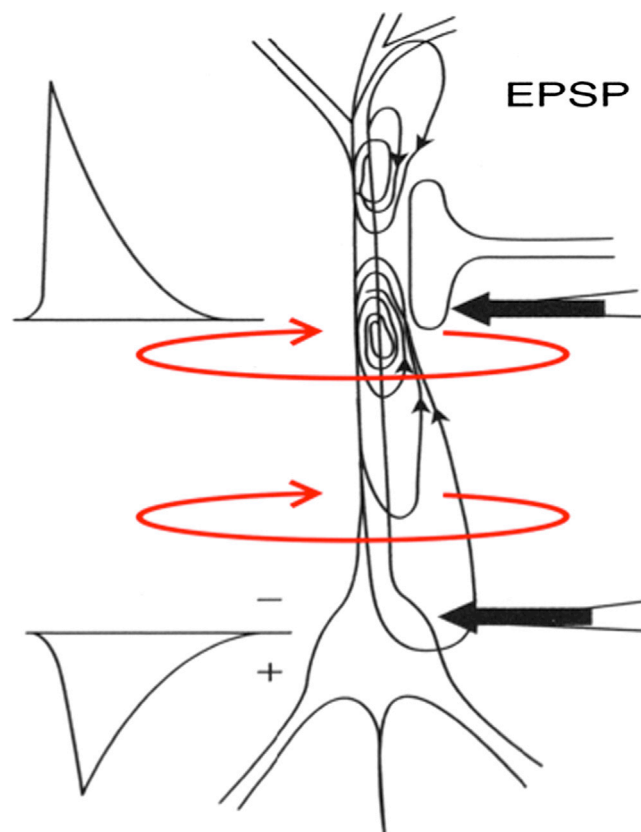


Figure 1. Neuronal Electrical and Magnetic Open Fields

Idealized pyramidal neuron showing intra- and extracellular current flow caused by synaptic activity: an excitatory postsynaptic potential (EPSP) located on an apical dendrite is associated with the flow of a net transmembrane positive current causing an extracellular active sink at the site of the synapse and a distributed passive source down to the level of the soma. Sink and sources are reflected in local field potentials (LFPs) of opposite polarity. Red ellipses represent the magnetic field generated by the intracellular soma-dendritic current. (Adapted with permission from Lopes da Silva, 2011a.)

perpendicular to the cortical surface. When these neurons are activated, intra- and extracellular currents flow; the longitudinal components of these currents (i.e., parallel to the main axes of the soma-dendritic tree) add, whereas their transverse components cancel. The result is a laminar current along the main axes of the neurons. The electrical field generated by the post-synaptic activity of a synchronously activated palisade of neurons is an open field, i.e., it can be detected at a distance from the neuronal sources. Simultaneously, magnetic field lines are created around the neuronal main axis (Lopes da Silva, 2011a; Hämäläinen et al., 1993) (Figure 1). In this way, local field potentials (LFPs) and local magnetic fields (LMFs) are generated. These form the building blocks of EEG and MEG signals, respectively. In general, we may state that the EEG reflects mainly the extracellular currents, while the MEG is more sensitive to the primary intracellular currents. In this context, the paper of Murakami and Okada (2006), in which it is demonstrated, in brain slices, how electrical activities of cortical neurons generate LFPs and LMFs is of special interest. Recent reviews of the physiology of extracellular fields and currents (Buzsáki et al., 2012)

and corresponding modeling studies (Einevoll et al., 2010) provide insightful reading.

2.2. Cortico-Scalp Transfer of EEG/MEG Signals

To reach the scalp, neuronal signals generated in the cortex must pass several layers of tissues with different electrical properties and a complex geometry. This implies that what is recorded at the scalp is an attenuated and transformed image of the cortical sources. This distortion has a stronger influence on the EEG than on the MEG because the cerebrospinal fluid, skull, and skin have different electrical conductivities that affect the electric fields but have much less influence on the magnetic fields since these tissues surrounding the brain have constant magnetic permeability.

The so-called forward problem consists in calculating the scalp electric field caused by neuronal sources. Using realistic models of the head based on MRI scans and applying actual values of skull-to-brain resistivity ratios, it is possible to solve the forward problem. In short, the solution of the forward problem in the case of the MEG is much less sensitive to the values of resistivity of the different shells surrounding the brain than in the case of the EEG.

The inverse problem of electroencephalography, i.e., the estimation of the sources from the scalp fields, is ill posed and without constraints has an unlimited number of solutions. This means that different combinations of intracerebral sources can result in the same potential distribution at the scalp. The common approach to tackle this problem is to make specific assumptions about the intracerebral sources (for example, equivalent current dipoles or layers of dipoles). An equivalent current dipole is a mathematical abstraction and it is just a rough model of the center of gravity of the cortical patch that is active at a given moment. The inverse estimation of the sources involves a numerical procedure, denominated “dipolar source localization” (DSL). Several alternative procedures were developed to circumvent the limitations of the equivalent dipole approach, namely “imaging methods” in which distributed current sources with specific constraints are estimated (Michel et al., 2004; Michel and He, 2011; Baillet, 2010).

Sampling EEG/MEG signals in space merits special attention. For most applications in neuroscience, the routine EEG recording with 21 electrodes is insufficient (Gevins et al., 1996; Nunez, 1995). Currently, many research systems consist of 128 electrodes. In some applications, 256 electrodes are used in so called dense-array EEG recordings (Holmes, 2008), what appears to be a practical maximum taking in consideration that all measurements are influenced by noise (Malmivuo, 2012). A thorough analysis (Ryynänen et al., 2006) of the relationship between scalp electrode density and spatial resolution of cortical potential distributions showed that, although the resolution increases with electrode density, this improvement is limited by the level of measurement noise: a good resolution at realistic noise levels is obtained with 128 electrodes and to improve this resolution significantly using 256 electrodes, the noise level has to be appreciably reduced accordingly. In all cases, the spatial sampling should be well adapted to the specific problem being studied. EEG dense arrays can be used to construct brain spatial maps in which the data of the whole set of sensors can be treated as a multivariate vector (Michel and Murray, 2012). With

respect to MEG, the modern whole-head MEG systems with 200 to 300 sensors provide dense enough spatial sampling for most applications (Hari, 2011; Hansen et al., 2010). A useful way of extracting information from EEG signals is to use independent components analysis (ICA) (Makeig et al., 1997), particularly as part of the preprocessing of these signals for further analysis. ICA is a powerful method that reduces the recorded channels to the minimum number of statistically independent EEG/MEG signals; furthermore, it can be very useful in identifying artifacts.

2.3. Comparison between EEG and MEG

EEG and MEG at the scalp reflect in essence the same elementary neuronal phenomena.

On the basis of a thorough comparison of EEG and MEG, Malmivuo (2012) concluded that these methods are only partially independent, such that recording both can yield some additional information on brain sources. Some differences, however, between the two methods should be pointed out.

- The EEG field is a scalar and a relative measurement; it is sensitive to both tangential and radial components of dipolar sources. Theoretically, a radially oriented dipolar source does not give rise to a magnetic field outside a spherical volume conductor; consequently the MEG is not sensitive to radial components of dipolar sources but to the tangential components (Ahlfors et al., 2010). The comparative accuracy of source localization in the brain with EEG and MEG was tested using implanted sources and found to be of the same order of magnitude (Cohen et al., 1990). The main advantages of MEG are its good spatial resolution in separating cortical sources due to less spatial smearing than in the EEG and its selectivity to activity of the fissural cortex (Hari, 2011).
- Differences and similarities between EEG and MEG are illustrated in Figure 2, where dipole density plots of equivalent dipolar sources of EEG and MEG data of α and μ oscillations are shown.
- Currently, a number of groups are investigating whether the combination EEG/MEG and fMRI may improve the identification of sources of activity in the brain (Schomer et al., 2000). Several investigations combined EEG recordings with fMRI to characterize the regions of the brain ("default brain network") during the resting state (Mayhew et al., 2013; de Munck et al., 2009) and in relation to epileptic networks (Gotman et al., 2006; Vulliemoz et al., 2010). Here we cannot deal with these innovative approaches in detail, but the reader may be referred to Valdes-Sosa et al. (2009) and Logothetis and Wandell (2004) for comprehensive reviews.

3. EEG/MEG: The Roots: Spike Firing, LFPs, and Synchrony

Neurons do not work in isolation; rather, they form dynamical assemblies that tend to work in synchrony, a concept popularized by Hebb (1949). A multitude of neuronal assemblies are usually simultaneously active in the brain, occupying different cortical areas. Neuronal assemblies that are functionally interconnected constitute a functional brain workspace, in the sense

proposed by Dehaene et al. (1998). The brain has to integrate distributed sets of neuronal assemblies spread over multiple cortical domains to achieve coherent representation of events and to effectuate coordinated actions. This means that the information processed by any neuronal population has to be synchronized with related populations. How is this achieved?

Buzsáki (2006, p. 174) points out that the most efficient way to establish synchrony in neuronal populations is by creating oscillations. The change from a random pattern of activity to an oscillatory mode in a neuronal population provides the conditions to modulate the membrane potentials in a population collectively. In general, the neurons that constitute those assemblies, pyramidal and interneurons, are interconnected by feedforward and feedback loops, where phasing inhibition plays a pivotal role. The dynamical behavior of these assemblies depends on the kinetics of ionic conductances, rise and decay of synaptic potentials, time delays, and the gains of neuronal circuits. These neuronal properties are controlled by neuromodulatory and biochemical variables (Amzica and Lopes da Silva, 2011). The existence of such feedforward/feedback loops favors the occurrence of oscillations; furthermore, many neurons, given the appropriate conditions, have intrinsic oscillatory properties that facilitate, or reinforce, the tendency for neurons in these loops to oscillate collectively.

Taking into consideration that LFPs are the building blocks of EEG/MEG signals, and that spike trains are essential in information transmission and processing in the brain, it is logical to examine how LFPs, and thus in an indirect way EEG/MEG signals, are related to spike firing. Here we select a small number of studies that support the notion that LFPs can have added value to spike trains in information encoding.

Jensen and Lisman (2000) showed that the hippocampus uses a neural phase code that depends on the relation between spike occurrence and phase of θ oscillations, as expressed in the LFP, in addition to the spike rate coding. Similarly, Montemurro et al. (2008) demonstrated that the phase at which neural firing occurs with respect to the period of an LFP oscillation in the visual cortex of monkeys conveys additional information beyond that conveyed by spike counts alone.

A similar kind of relation between LFPs and spike firing has been shown to exist in the case of motor programming. Murthy and Fetz (1996) found in the motor cortex that cortical neurons can become synchronized specifically during LFP oscillations, even if spikes are uncorrelated during nonoscillatory periods. This indicates that the oscillatory behavior plays a role in promoting the synchronization of the neuronal units, through a process of phasing inhibition.

In a comprehensive review of the functional significance of LFPs, namely γ oscillations, Fries (2009) and Fries et al. (2007) state that the adjustment of spike timing by the γ cycle is not an epiphenomenon but a fundamental mechanism in cortical information processing.

Summarizing, LFPs/LMFs may contribute to information coding in the brain. Given that EEG/MEG signals reflect LFPs/LMFs, it may be extrapolated that EEG/MEG signals may also reflect information coding in the brain, although the filtering that takes place as LFPs/LMFs are transferred to the scalp results in some loss of specific information.

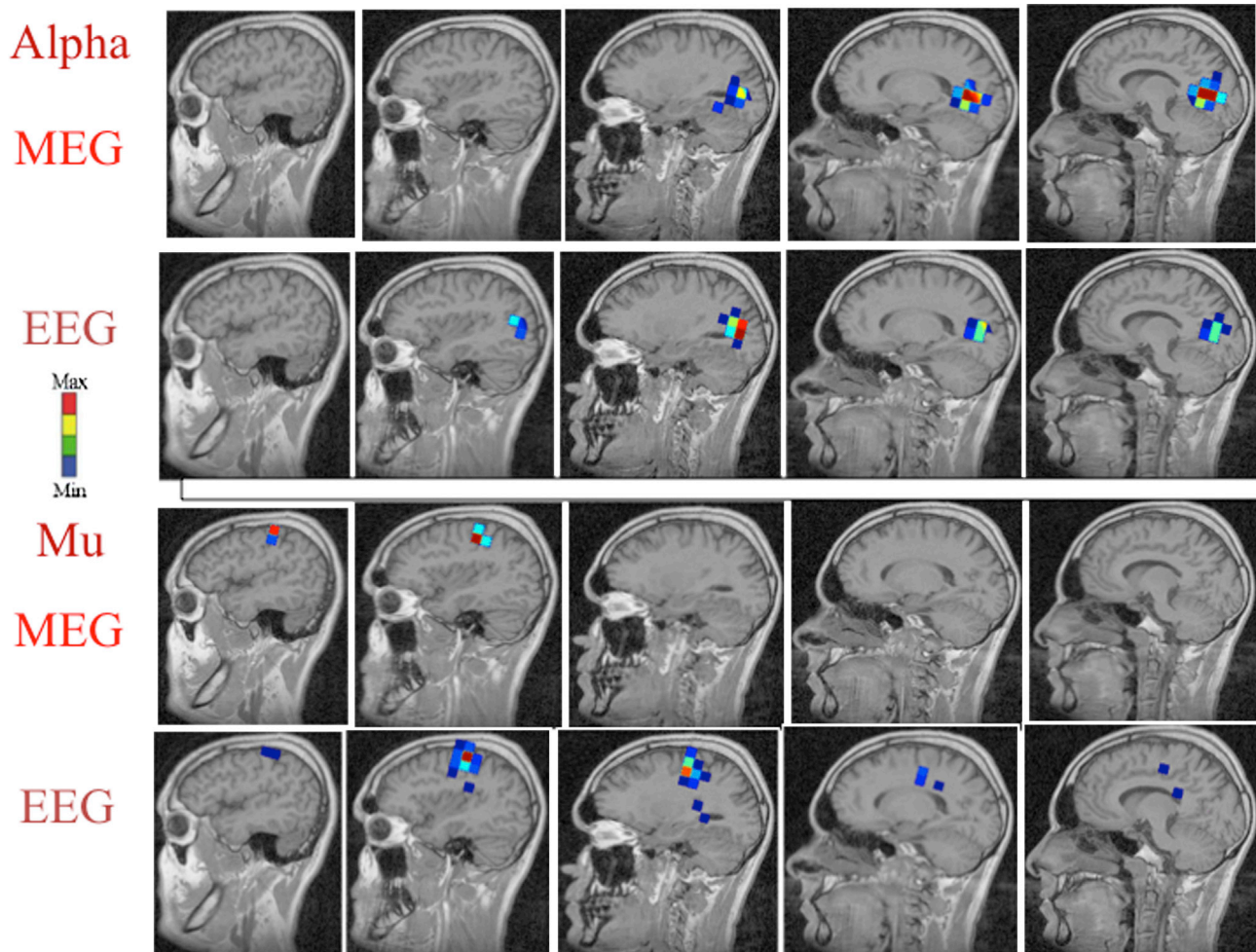


Figure 2. Spatial Distribution of EEG/MEG α and μ Dipolar Sources

Dipole density plots of EEG and MEG sources of α and μ oscillations superimposed on MRI slices of the same subjects (most medial on the right side). Voxels where significant amounts of equivalent dipolar sources are localized are represented in color, from red for those that contain the highest density of sources ("hot spots"), and in decreasing density, orange, yellow, and light and dark blue. Note that the MEG clusters of the somatosensory μ rhythm have a very strict localization, while the corresponding EEG clusters are more widespread on the cortical surface. The main visual α "hot spots" of the EEG sources are localized in a more lateral MRI slice than those of the MEG, what likely results from the curvature of occipital cortical surface such that the dipolar sources located at the medial cortical surface have mainly tangential orientations, while those located on the convexity of the occipital pole have mainly radial orientations. This contrast reflects the different sensitivity of the MEG and EEG to tangential and radial dipolar orientations. (Adapted with permission from Manshanden et al., 2002.)

4. EEG/MEG Oscillations: Signal Properties and Interactions

4.1. The Relevance of the Frequency of Oscillations

EEG/MEG oscillations occur at different frequencies from the infraslow, say 0.2 Hz, to the very fast, reaching values of several hundreds of hertz. In general, oscillations at the lower end of the frequency spectrum tend to engage large spatial domains, while those at higher frequencies are localized in restricted cortical areas. With the risk of oversimplifying, we may state that the slow oscillations are particularly suited to set a functional bias throughout a large population of neurons, as occurs in "up and down states" of slow waves (Steriade, 2006). Oscillations at intermediary frequencies, such as in the θ and α ranges, are optimal to modulate, or to gate, the transfer of information across specific populations, such as those of the hippocampal formation and associated cortical areas in the case of θ (Mizuseki

et al., 2009) and of thalamocortical systems in the case of α (Amzica and Lopes da Silva, 2011). Oscillations at the higher frequencies, in the β and γ range, are especially adequate to engage relatively discrete populations in achieving transfer of packets of specific information (Freeman, 2003) among neuronal assemblies. Thus, specific oscillations have different kinds of functional connotations. Most often oscillations at different frequencies work in a cooperative, integrated way.

4.2. How to Assess Functional and Effective Connectivity?

EEG/MEG signals, per se, may yield information of interest in neurocognitive studies but a most essential aspect is how these signals interact. To characterize these interactions, Friston et al. (2013) proposed two terms: functional and effective connectivity. The former accounts for the statistical association between two neuronal activities; the latter accounts for the causal influence of

one system on another one. A variety of methods of signal analysis to estimate functional connectivity exist (Lachaux et al., 1999; Stam et al., 2007; Wendling et al., 2009; Vinck et al., 2011; Haufe et al., 2013), among which the phase-locking value (PLV) is currently the most widely used. In any analysis of connectivity based on EEG/MEG signals, one has always to take into account the pervasive influence of volume conduction by means of which a given activity may be simultaneously recordable at different sensors that can lead to ambiguous interpretations. In this context, simple phase data, especially in the case of coexisting multiple sources, must be analyzed very carefully, as done by Sirota et al. (2008) in an analysis of hippocampal and extrahippocampal θ activities in the rat. Whenever possible, it is important to measure time delays (estimated from the slope of phase versus frequency plots) between EEG/MEG signals since physiological signals need time to propagate from brain site A to brain site B (for specific methodologies, see Boeijinga and Lopes da Silva, 1989; Axmacher et al., 2008; Friston et al., 2012; Ewald et al., 2013). This is important for two main reasons. First, if there is a time delay between two EEG/MEG signals different from zero, the influence of a common electric/magnetic volume conducted field may be questioned. Second, the determination of time relations between different EEG/MEG signals is important to better understand the dynamics of the interactions between distinct brain systems, i.e., to determine which are the drivers and which are the followers.

With the same general objective, some investigations apply dynamic causal models and Granger causality to estimate effective connectivity (Friston et al., 2013; David, 2011; Roebroeck et al., 2011), but such models have simplified parameter spaces, such that their constructive and predictive values are limited. These models should be validated with data obtained at the micro- and mesoscopic levels, including recordings of spike series and LFPs. This field is evolving swiftly, but more basic research combining different levels of analysis of the neuronal networks is needed. At an abstract level, the complex relations between EEG/MEG signals have also been described using the conceptual tools of mathematical graph theory with the objective of characterizing large distributed brain networks in terms of interconnected nodes and hubs (Stam, 2010).

5. EEG/MEG and Cognitive Processes

In this section, we discuss the role of EEG/MEG oscillations in different classes of processes: coding of information with respect to perception and memory, modulating brain attentional systems, transferring information, and the organization of memories.

5.1. EEG/MEG Oscillations: Role in Perception and Memory

5.1.1. What Makes Gamma Oscillations Special? The term “gamma” (γ) is generally used for frequencies between 30 and 90 Hz (Buzsáki and Wang, 2012), while the term “high-frequency oscillations” (HFOs) describes those beyond 90 Hz. The exact frequency band of any EEG/MEG oscillation should always be duly specified, since the boundaries between EEG/MEG frequency bands, particularly in the high-frequency ranges, are not well defined.

Gamma oscillations play a functional role in the formation of neural representations of events, i.e., in perception, as demon-

strated in the visual cortex (Eckhorn et al., 1988; Gray et al., 1989; Singer and Gray, 1995). From these seminal observations emerged the hypothesis that the synchronization between neurons binds them together to constitute functional assemblies. This mechanism constitutes the substrate of the “binding hypothesis” proposed by von der Malsburg (1999) to account for the formation of a perceptual “gestalt.”

Both single-unit activity and local field EEG/MEG records in the visual cortex can exhibit oscillations in the γ frequency range (Figure 3). Fries et al. (2001) showed that the coherence between spikes in visual cortex neurons of the monkey and LFP γ oscillations increased when the animal shifted attention to the receptive fields of the recorded neurons, compared with the condition in which attention was directed away from the receptive field. As mentioned above, the enhancement of γ LFP-spike field coherence promotes the increase of spike synchrony in a neuronal population; a consequence is that the latter may be more efficient in activating other neuronal populations to which those spikes project, what constitutes the basis of the “communication through coherence” hypothesis (Womelsdorf and Fries, 2007).

Furthermore, γ oscillations can work as the carrier mechanism of “phase coding,” where the stronger the stimuli, the earlier the phase relative to the γ cycle at which spikes occur (Fries et al., 2007). These are momentous hypotheses that need further experimental scrutiny and are the subject of relevant controversies (Gray, 1999; Roelfsema et al., 2004; Ray and Maunsell, 2010; Ni et al., 2012).

Some previous studies put in evidence conspicuous γ oscillations in other brain areas, namely in the olfactory system of the rabbit, ranging from 40 to 80 Hz, associated with odor stimulation (Freeman, 1978), and also in cat and rat (Bressler and Freeman, 1980), while Bouyer et al. (1982) described γ oscillations around 40 Hz in the somatosensory cortex of the cat and Bragin et al. (1995) in the hippocampus of the behaving rat.

5.1.2. Gamma Oscillations or γ -Band Activity at the Scalp: Some Caveats. In the Introduction, we underscored that the identification of a brain oscillation implies demonstrating that there is a spectral peak within the frequency band of interest. In the case of γ , many studies report that there are changes in power over a wide band without indicating clearly whether one or more spectral peaks do exist. Another complication in interpreting γ activities at the scalp is the possibility that artifacts caused by spike potentials associated with microsaccades may contaminate EEG recordings, contributing to the power of the γ (30–100 Hz) frequency band (Yuval-Greenberg et al., 2008). The criticisms of Yuval-Greenberg et al. (2008) triggered an open controversy (Fries et al., 2008; Melloni et al., 2009). This kind of artifact may also contaminate intracranial EEG (Jerbi et al., 2009; Kovach et al., 2011) and MEG (Carl et al., 2012) recordings, although to a lesser extent. In any case, the use of fast eye trackers and recording the radial EOG as control signal is recommended. In general, scalp EEG Laplacian derivations may be helpful to reduce this and other artifacts.

5.1.3. Is There Evidence that γ Associated, or Not, with Other Oscillations Encodes Perception and Memory in Human? In human, a number of EEG studies attempted to corroborate in a global sense the experimental findings obtained in the monkey and the cat, mentioned above.

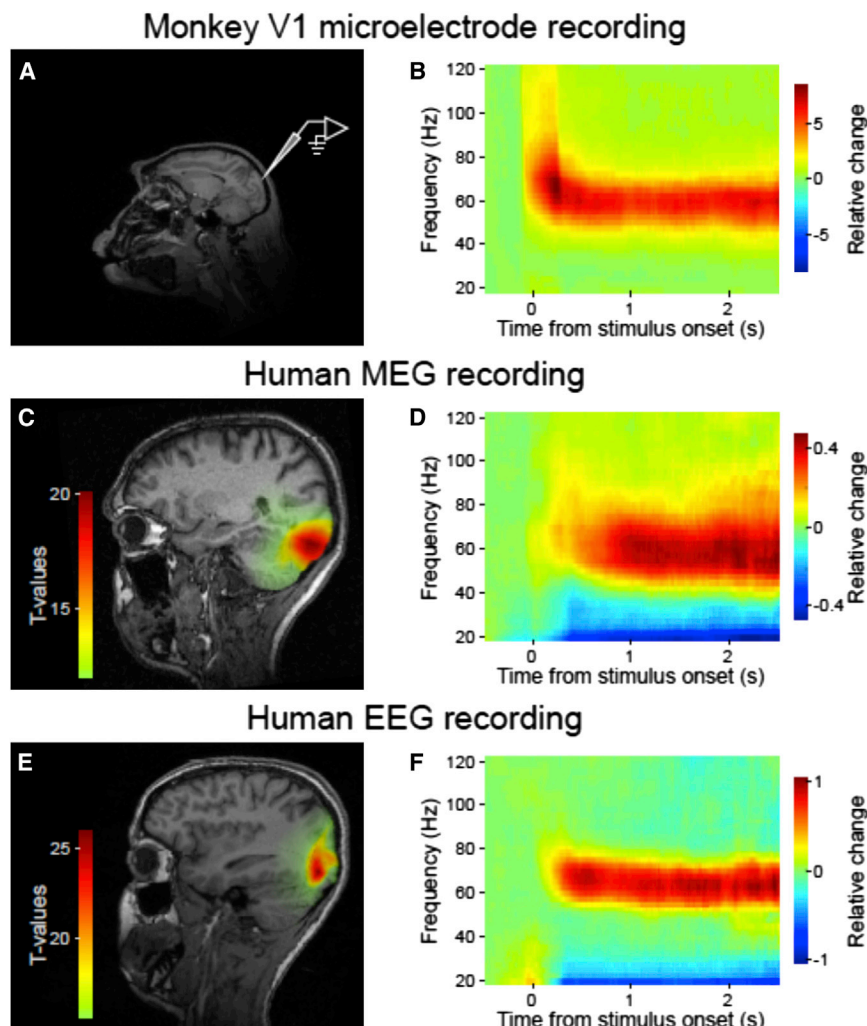


Figure 3. Neuronal γ Band Assessed with Micro and Macro Techniques

Synchronized induced γ -band activity lasting a few seconds in monkey and human showing the location of the main estimated cortical sources (left) and the corresponding time-frequency plots (right).

(A and B) Microelectrode recording from the visual cortex of an awake macaque monkey.

(C and D) MEG recording in a human subject

(E and F) EEG recording in another subject. (Adapted with permission from Fries et al., 2008.)

of γ -band activity have been found using scalp EEG (Tallon-Baudry et al., 1998) or intracranial EEG (Sederberg et al., 2007a, 2007b; Axmacher et al., 2008). In the latter study, EEG HFO in the frequency band between 80 and 120 Hz was analyzed.

5.1.4. EEG/MEG θ Oscillations and Cross- θ / γ -Phase Coupling: An Integrated Mechanism Enabling Memory Processes? Comprehension of the role of θ rhythmic activities in cognitive processes has been built up on experimental animal research and, besides some scalp EEG and MEG studies, also on investigations carried out in epileptic patients in whom intracranial electrodes were placed for diagnostic purpose. The latter studies showed a close relation between θ power and memory processes, focusing on activities of the hippocampus and associated brain areas (Arnolds et al., 1980; Raghavachari et al., 2006; Kahana et al., 2001; Sederberg et al., 2003;

A classic example is the study of Rodriguez et al. (1999), showing an enhancement of phase synchrony between several EEG derivations at the γ frequency when subjects recognized an upright “Mooney” face, in contrast with when the face was presented in an inverted position and was not recognized by the observers. Rodriguez et al. (1999) reported results that they interpreted as demonstrating a specific role of EEG γ activity in human visual perception. Trujillo et al. (2005) confirmed these findings but emphasized that the results depend on the frequency and reference chosen.

The Trujillo study, although it appeared to be at variance with respect to the Rodriguez study, reinforces the hypothesis that phase synchronization within the γ frequency band is associated with conscious perception.

Along the same line, several investigations using EEG/MEG signals have been published supporting the assertion that neurophysiological processes mediating conscious perception involve transient increases of phase synchrony of oscillations in the γ band (Tallon-Baudry et al., 1996; Melloni et al., 2007; Doesburg et al., 2009; Fahrenfort et al., 2012). Also in memory tasks in which items have to be held in short-term memory, increases

Caplan et al., 2003; Rizzuto et al., 2003; Axmacher et al., 2008; see reviews by Mitchell et al., 2008; Jacobs and Kahana, 2010). One pertinent question is in how far these intracranial features of θ oscillations are also manifest at the level of the scalp. In this respect, “frontal-midline θ oscillations” in human scalp recordings (Gevins et al., 1979) associated with the performance in various cognitive tasks have also been described. However, the exact origin of these θ activities, and the underlying neuronal sources, were not yet precisely demonstrated in these clinical studies, although in the rat θ oscillatory LFPs locally generated in the prefrontal cortex (PFC) have been recorded (Siapas et al., 2005; Jones and Wilson, 2005). The functional significance of θ rhythmic activities for memory processes is reviewed by Sauseng et al. (2010).

In order to get insight into the underlying mechanisms, it is important to note that this kind of oscillation does not occur in isolation. This is clearly demonstrated by the study of Sauseng et al. (2009), who, using scalp EEG, found in visual memory tasks that the retention of information was associated with the occurrence of θ rhythmic activity modulating γ oscillations at posterior parietal sites. Synchronization of γ phase to the peak

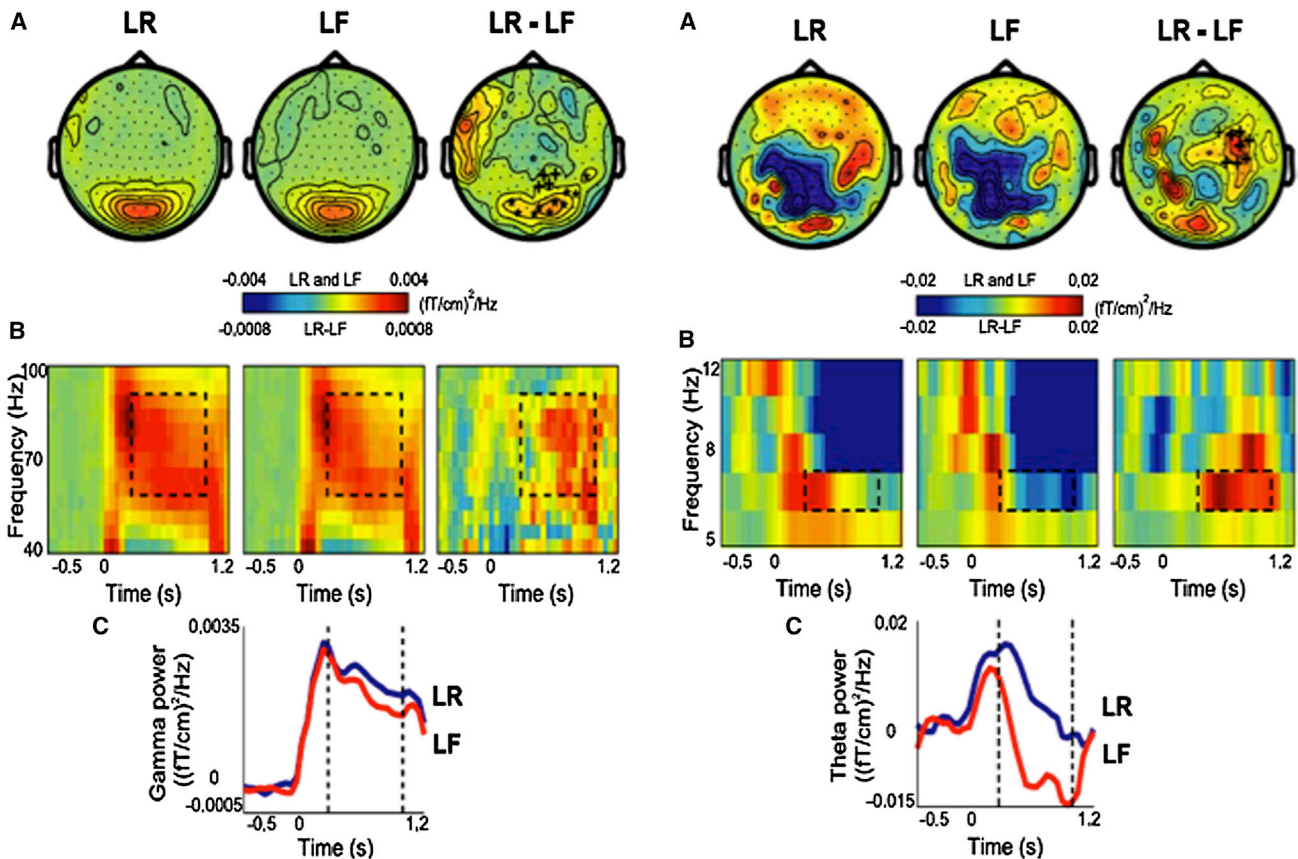


Figure 4. γ and θ/α Activities during Memory Encoding

MEG was recorded while subjects performed a memory task; the results of the encoding period are shown for two frequency bands: γ on the left, and θ and α on the right, since these showed the most conspicuous effects with respect to the late remembered (LR) and late forgotten (LF) items. The increases in γ are mainly seen in occipital areas, while θ increases are rather localized to right temporal area (LR-LF). The differences between the two conditions (LR - LF) were significant for both γ and θ ; the decrease in α (plots on the right) was conspicuous but not different in the two conditions. (Adapted with permission from Osipova et al., 2006.)

of θ oscillations was increased contralaterally to the visual hemifield containing relevant items to be retained in memory, while α power increased ipsilaterally what may cause suppression of irrelevant information (see 5.2.2). Whether this θ is locally generated in the cortex or is volume conducted from the hippocampus is an issue that merits further analysis.

There is experimental evidence that oscillatory processes encoding perception and memory often involve a combination of different types of oscillations. The hypothesis has been put forward that cross-frequency phase coupling may play a significant role with respect to cognitive processes (Palva et al., 2005; Jensen and Colgin, 2007). An interesting demonstration of this phase-coupling is provided, for example, by the investigation of Osipova et al. (2006), who found an association between encoding/retrieval of memorized items and the power of oscillatory activity in two frequency bands: γ (60 to 90 Hz) and θ (4.5 to 8.5 Hz) (Figure 4). It is important to note that multivariate methods of analysis should be preferred to reveal phase and amplitude cross-frequency coupling as proposed by Canolty et al. (2006, 2012).

These findings reinforce the notion that oscillatory coding plays a role in memory processing, particularly encoded by the emergence of γ -band activity integrated with θ oscillations.

5.2. EEG/MEG Oscillations Setting and Modulating Brain Functional States: Role in Attention

5.2.1. Cortical α , Thalamic Nuclei, the Pulvinar Nucleus, and Attention. Besides the classic α rhythm of the visual cortex, there are rhythmic activities in the same frequency range that can be recorded from the sensorimotor cortex (called the mu rhythm) and the temporal cortex (called the tau [τ] rhythm) (Niedermeyer, 1990, 1997; Tiihonen et al., 1991). Occipital α waves are usually conspicuous as visual attention is reduced, while μ rhythms of the sensorimotor cortex occur as the subject is in a state of muscular relaxation. Furthermore, the coherence of α waves within the visual cortex is widespread (Lopes da Silva et al., 1980) leading to the conclusion that horizontal intracortical connections are important in spreading α activities throughout cortical domains. The cortical generators of α oscillations were found in dog (Lopes da Silva and Storm Van Leeuwen, 1977) and in monkey (Bollimunta et al., 2008, 2011) to have the configuration of layers of parallel dipolar sources that correspond to active pyramidal neurons of cortical layers IV/V arranged in a palisade-like manner. A remarkable novel finding (Spaak et al., 2012) is that γ -band oscillations in superficial layers of the monkey visual cortex are modulated

by α oscillations in deep layers (Figure 7), as discussed later in section 5.2.4.

Several experimental investigations showed that α oscillations can be recorded in thalamic nuclei at the same time as in the cortex (Lopes da Silva et al., 1980). Thalamic nuclei form an essential part of cortico-thalamo-cortical loops that constitute a complex set of nested (feedforward and feedback) loops, involving different subpopulations of cortical neurons and thalamic neurons, including those of the reticular nucleus (Steriade, 1999), that sustain α oscillations (Steriade et al., 1990). The core circuit consists of the connections between GABAergic cells of the reticular nucleus that receive collaterals of both (1) thalamocortical fibers from the relay cells (TCR) and (2) corticothalamic descending fibers from cortical neurons. The reticular GABAergic cells project back to the sector of the particular thalamic nucleus from which they receive inputs (Jones, 2009). The dynamical behavior of these circuits can lead to the generation of α oscillations through interacting inhibitory-excitatory re-entrant connections. In addition, the intrinsic oscillatory properties of TCR cells (high-threshold cells; Hughes et al., 2011) and of cortical pyramidal neurons of layer V (Silva et al., 1991) are also important in the generation of α oscillations. This activity is strongly influenced by nonspecific brain stem systems, in particular by cholinergic modulating systems that control the state of vigilance and attention.

The relation between thalamic nuclei, α activity, and attention has received a boost with the demonstration, in the monkey, that the modulation of α rhythms depends on the activity of neuronal populations in the Pulvinar nucleus of the thalamus (Saalmann et al., 2012), related to the attentional state of the animal.

5.2.2. Coupled Changes of α Oscillations in Opposite Directions Can Occur in Different Systems. α oscillations recorded from the scalp of different subjects may display different peak frequencies. Factor analysis of scalp EEG (Lopes da Silva, 2011b) has systematically put in evidence two α components: “low α ” = 8–10.5 Hz, and “high α ” = 10.5–12.5 Hz, although these limits vary slightly among studies. Klimesch (1999) noted that the reactivity of α is not a unitary phenomenon. In general, widespread “low α ” power decreases in response to a variety of alerting or warning signals, while changes of “high α ” are topographically more restrict and are mainly induced by the cognitive processing of stimuli. In general, the frequency of α rhythmic activities is faster at posterior than at anterior sites. The dynamics of α oscillations depend not only on frequency but also on brain area, such that increases of α power in one particular area can appear simultaneously with decreases in another area. This phenomenon has been demonstrated in a number of experimental situations (Palva and Palva, 2011). Here we consider two cases.

(1) Decreases or increases of $\alpha(\mu)$ power can occur in association with voluntary movements. Because such phenomena may be interpreted as due to changes in the degree of synchrony of underlying neuronal networks, the former has been called event-related desynchronization (ERD) and the latter event-related synchronization (ERS) (Pfurtscheller and Aranibar, 1977). ERD and ERS can occur at the same time in different cortical areas. Associated with a voluntary hand movement, there is a decrease in power—ERD—of the sensorimotor activity

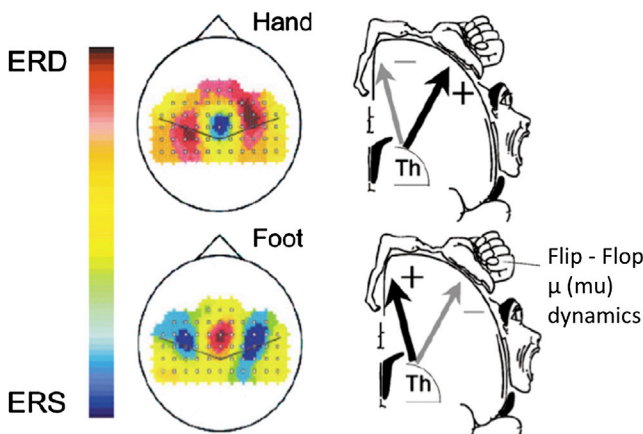


Figure 5. Focal μ -Rhythm ERD and Surround ERS

Maps display ERD and ERS during voluntary movement of the hand (top) and movement of the foot (bottom). Note that when attention is focused on the hand movement, there is μ ERD over the cortical areas representing the hands (and supplementary motor area) and simultaneously μ ERS over the cortical area in the midline representing the inferior limbs. In contrast, the situation in which attention is paid to the feet causes a mirror image of ERD-ERS. The motor homunculus with a schematic mechanism of cortical μ oscillations activation/deactivation gated by thalamic structures is shown on the right. Color code: red indicates power decrease or ERD, and blue indicates power increase or ERS. (Adapted from Pfurtscheller and Lopes da Silva, 1999.)

in the α band (μ rhythm) recorded over the cortical area where the hand is represented, while there is an increase in power—ERS—within approximately the same frequency band over the area representing the inferior limbs; the opposite effect is encountered when the voluntary movement is that of the foot, as illustrated in Figure 5. This phenomenon may be called “focal ERD, surround ERS” of μ dynamics (Pfurtscheller and Lopes da Silva, 1999; see Suffczynski et al., 2001 for a computational model of this phenomenon). Similarly Jones et al. (2010) found, using MEG recordings, that in cases in which subjects had their attention cued to the hand, there was a decrease (ERD) of μ power over the contralateral cortical hand area, while in case attention was cued to the foot there was an increase of μ power (ERS) over the hand area.

The same phenomenon is also observed between different modalities, namely between sensorimotor cortex μ activity and occipital cortex visual α using scalp EEG (Anderson and Ding, 2011).

Also, Popov et al. (2012) in an MEG investigation of the perception of faces expressing emotional (fear or happiness) or neutral states, found that changes from neutral to emotional faces were associated with α - β (10–15 Hz) power increase in sensorimotor areas, whereas there was a decrease in the visual cortical areas.

(2) There is ample experimental evidence showing that ERD/ERS is not restricted to the sensorimotor cortex. It has been shown as well in the visual cortex even with a retinotopic spatial distribution (Kelly et al., 2006; Rihs et al., 2007). Several studies showed that when attention is directed toward one visual hemi-field, there is a decrease (ERD) of α power over the parieto-occipital areas contralaterally and an increase (ERS) ipsilaterally (Worden et al., 2000; Thut et al., 2006; Medendorp et al., 2007).

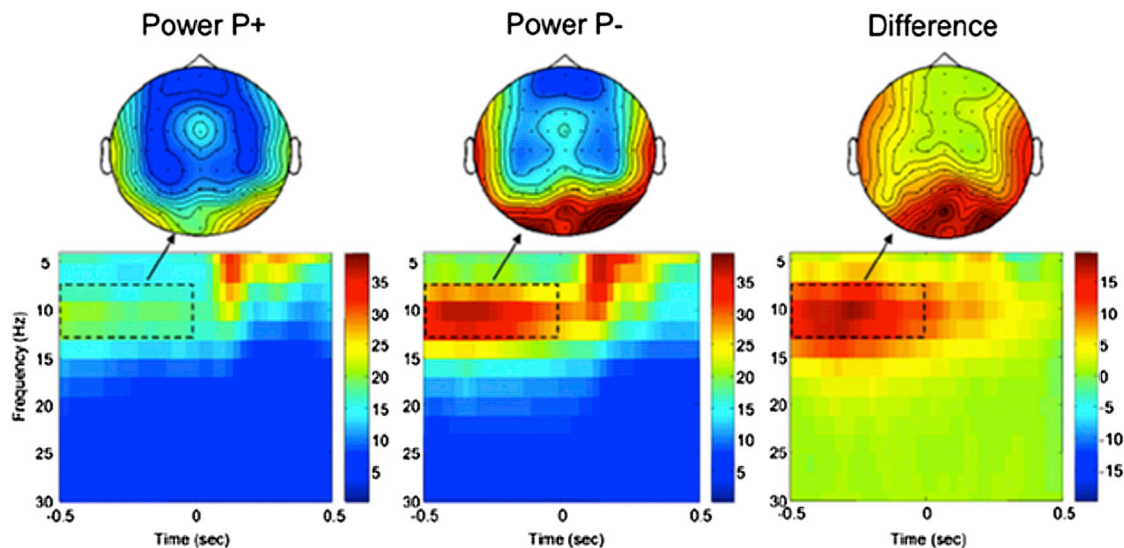


Figure 6. Prestimulus α Power Predicts Visual Perception Performance

Prestimulus α (8–12 Hz) oscillations predict visual perception performance. Time-frequency plot of power is shown for the electrode O2. Stimulus is presented at time 0. Visual stimuli near threshold were presented to the subjects. In some trials, the stimuli were adequately detected: group of perceivers (P+); those cases in which the stimulus was not perceived constitute the group of nonperceivers (P–). Note that α power in the period preceding the stimulus is significantly different between the two groups; it is much stronger in the case of the P– compared to the P+ group. (Adapted with permission from [Hanslmayr et al., 2007](#).)

This “flip-flop ERD/ERS phenomenon” can be interpreted as follows: the brain systems where α ERD occurs are those that receive focal attention; the decrease of α power results in a disinhibition of the local population, such that information processing in this population is enabled or facilitated. Simultaneously, α ERS occurs in other systems that are out of the attentional focus; here the increase in α power exerts an inhibitory action and thus depresses the influence of distractors.

In this way, α modulation can be a mechanism to optimize signal-to-noise ratio promoting the conditions for efficient information processing ([Jensen and Mazaheri, 2010](#); in line with [Klimesch et al., 2007](#); [Klimesch, 2012](#)).

5.2.3. α Oscillations Are Not “Idling Rhythms”: Their Role in Attention and the Importance of Phase. That α rhythm does not represent an “idling” state of the brain is strongly supported by studies showing that perception is modulated by the state of α oscillations. This emerges from several studies: [Ergenoglu et al. \(2004\)](#) recorded the EEG while presenting visual stimuli to human subjects at an intensity near threshold. These authors found that in cases in which stimuli were properly detected, the α power in the prestimulus EEG was significantly lower than in cases in which this did not happen. These results were corroborated and further extended by [Thut et al. \(2006\)](#) and [Hanslmayr et al. \(2007\)](#), who showed that the state of prestimulus ongoing α oscillations can predict whether a visual stimulus will be perceived or not ([Figure 6](#)). In addition to the role that the α state has in modulating the threshold for perception, there is also experimental evidence that the phase of α oscillations also modulates information processing. This may be concluded from the study of [Mathewson et al. \(2009\)](#), who showed that the phase of EEG α rhythm can reliably predict subsequent detection of visual stimuli and stressed that α power increases represent a form of “pulsed inhibition” of cortical excitability that modulates

the awareness state. This is in line with the experimental observations, in the monkey, that cortical multiple-unit activity is modulated by local α oscillations ([Bollimunta et al., 2008](#)).

Another approach to investigate whether the phase of α oscillations plays a role in the perception of visual stimuli is that of [Dugué et al. \(2011\)](#). These authors applied low-intensity transcranial magnetic stimulation (TMS) to the visual cortex, which can evoke phosphenes in a fraction of trials. They found that whether phosphenes were evoked or not depended on the phase of the ongoing α oscillation at the moment of stimulation. This is evidence for a causal relation between the phase of the α oscillation, the cortical excitability state, and the resulting visual perception. Thus, α oscillations modulate “windows of excitability,” as [Dugué et al. \(2011\)](#) expressed.

In this respect, the study of [Haegens et al. \(2011\)](#) is particularly relevant. These authors investigated LFPs and spike firing in different cortical areas (somato-sensory, motor, and premotor areas) in monkey, performing a vibrotactile discrimination task. They found that spikes tended to occur at the trough of an α cycle, and as the amplitude of alpha oscillations decreased, the firing frequency increased, supporting the notion that α oscillations exert an inhibitory modulating influence. In addition, α power was inversely related to performance, demonstrating that a decrease of α oscillations enables performance, while an increase of α exerts an inhibitory influence.

A catching approach to test whether α rhythmic activity correlates in a quantitative way with the degree of attention consists in manipulating the latter pharmacologically and to determine whether both variables, α activity and attentional processing, covary significantly. This was reported by [Bauer et al. \(2012\)](#), who administered the cholinergic drug physostigmine to normal subjects whose MEG was being recorded. Physostigmine enhanced attention as manifest in a better task performance

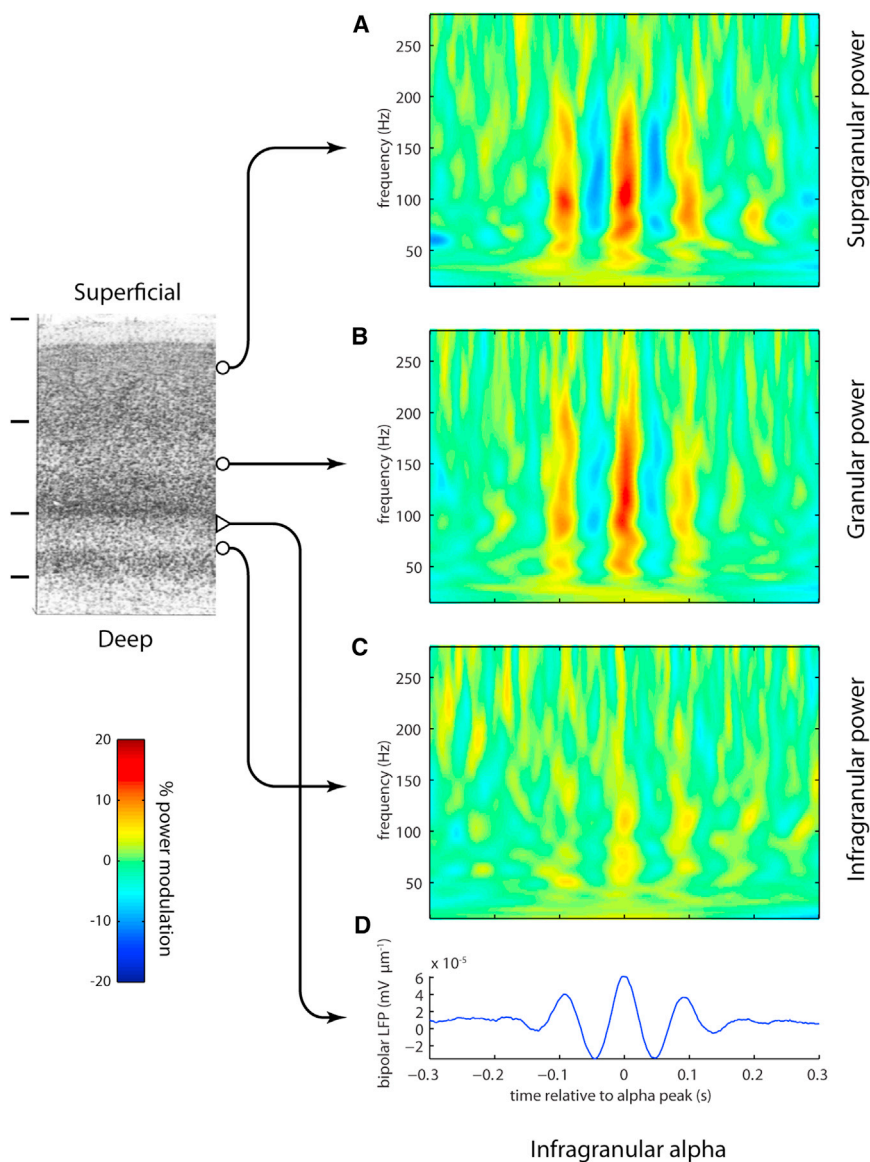


Figure 7. Intracortical Distribution of γ Power Time Locked to the Peaks of α Rhythm

Recording from the monkey primary visual cortex using 24 contact laminar probes showing γ activity in the superficial layers and α in deep layers. Time-frequency plots are shown for three cortical layers. The power of γ (50–200 Hz) activity is locked to the peaks of the deep α rhythm. The plots show the modulation of gamma power phase locked to the α oscillations, in the two superficial layers but not in the infragranular layer. (Adapted with permission from Spaak et al., 2012.)

lation is inhibitory, as suggested by the alpha-inhibition hypothesis proposed by Klimesch et al. (2007). The fact that this stimulation facilitates perception ipsilaterally is in line with the common phenomenon that increases of α power in one particular area appear simultaneously with decreases in another area, as discussed also in section 5.2.2.

These findings are sufficient to eradicate the concept, still often expressed, that alpha would be an “idling rhythm,” an idea that has been rightly challenged (Niedermeyer, 1997; Basar et al., 1997; Quiroga and Schürmann, 1999).

5.2.4. Opposite Changes of α and γ Oscillations. We mentioned above that in a number of studies a remarkable interplay between decreases of α and increases of γ has been put in evidence. Siegel et al. (2008), using MEG in a spatially cued motion discrimination task, found that attention induced a reduction of α oscillations (and also β) in the hemisphere representing the attended hemifield, followed by enhancement of γ activity. Most interesting, the stronger this effect was, i.e., α decrease combined with γ increase, the

and, at the same time, it amplified the associated change of α power, relative to the placebo condition; statistically, both effects were significantly correlated.

With the purpose of finding experimental evidence for a causal relation between α oscillations and cognitive processes, a technique that is being used in several situations (see also 5.3.2) consists in mimicking the natural brain oscillation by applying rhythmic pulses by means of TMS at a frequency typical of a brain oscillation and determining whether this manipulation causes any changes in a specific cognitive process (Thut et al., 2011). Indeed, TMS applied to the occipital or parietal cortex at the α frequency (10 Hz) (but not at 5 or 20 Hz), prior to the presentation of lateralized visual stimuli, was shown to impair visual detection contralateral to the stimulated side, while enhancing detection ipsilaterally (Romei et al., 2010, 2012). These findings show that the α -specific oscil-

more likely the subjects would successfully complete the required task. This observation strengthens the concept that these combined changes in α and γ oscillations have functional relevance with respect to the subjects' behavioral performance. Furthermore, Spaak et al. (2012) observed what may be called “nested oscillations” in the monkey visual cortex, where there is a layer-specific phase coupling between α rhythm phase and γ power (in two bands: 30–70 and 100–200 Hz), with the α oscillation of the deeper cortical layers modulating the γ oscillation of the superficial layers (Figure 7). This finding further supports the interpretation that α oscillations exert a phasic modulation of cortical information processing in a top-down manner.

The conclusion may be drawn that α oscillations play an important role in the control of attention, acting as a sort of traffic controller of information flow within the cortex.

5.3. EEG/MEG Oscillations and Transfer of Information: Memory Consolidation

5.3.1. How Can Memory Consolidation Be Modulated by Sleep? Slow oscillations with dominant frequency around 0.5–1.0 Hz are generated in the cortex. Steriade (1999) demonstrated that these slow waves consist of a succession of “down states” and “up states.” During down states, cortical neurons are hyperpolarized and do not display firing; during up states, these are depolarized. This slow oscillation is the manifestation of a dynamical brain state that operates as a widespread modulating process that can enable or disable the flow of signals encoding memory events. A number of studies showed that slow-wave sleep enhances memory retention, namely a night sleep can enhance the capacity of subjects retrieving the information that they memorized before sleeping (Walker and Stickgold, 2006). There is solid experimental evidence to support the contention that slow-wave sleep plays an active role in promoting the conditions for the consolidation of memories (see for details Rasch and Born, 2013).

5.3.2. Correlation or Causality of the Infraslow Oscillation and Memory Tested by External Manipulations. A pertinent question is whether a causal relation between infraslow oscillation and memory processes may be established. This was tested experimentally by Marshall et al. (2006), who showed in human subjects that slow oscillations induced by TMS at low frequency (0.75 Hz) during non-REM sleep were able to improve the retention of hippocampus-dependent memory; in contrast, stimulations at higher frequencies (5 Hz) were not effective. This supports the concept that the slow oscillation fulfills an enabling function with respect to the process of encoding memorized information.

If we attribute to the slow oscillation an enabling function of this kind, we have to consider what is the nature of the process that is being enabled. The latter should be a process that is responsible for encoding memories as such. Since during the “up state,” high-frequency ripples (about 200 Hz) and 12–14 Hz spindles (Clemens et al., 2005) occur preferentially, these oscillatory phenomena may be mediators of the transfer of information from the hippocampal formation to the neocortex, leading to the storage of information in the neocortex. In particular, “ripples” appear to be potential candidates (Buzsáki, 2006, pp. 342–355). The idea that ripples may fulfill such a function is supported by the findings of Girardeau et al. (2009) and Ego-Stengel and Wilson (2010), who showed in the rat that disrupting selectively ripple oscillations impairs spatial learning. This implies that “ripples” and spindles may be operational in encoding information to be memorized.

5.4. EEG/MEG Oscillations— α , β , γ , and Motor Behavior—ERD, and ERS

It has been known for some time that, in human, oscillations around 40 Hz occur during voluntary isometric contractions that were denominated as the Piper rhythm (Brown et al., 1998). These oscillations can be recorded in the electromyogram (EMG) from peripheral muscles. A momentous finding was the discovery that in the MEG, recorded from the hand area of the contralateral motor cortex, oscillations were recorded that showed significant coherence with the peripheral EMG oscillations of the arm. The dominant frequency of the MEG oscillations

could vary between 30 and 60 Hz (Salenius et al., 1997; Brown et al., 1998). The conclusion from these observations is that the muscular Piper rhythm is driven by an oscillatory activity in the contralateral motor cortex and that the frequency of the oscillation varies with the strength of the muscular contractions.

Regarding the association of EEG/MEG signals with planning and execution of movements, we may consider a very simple movement of the hand, for example, performed in response to a cue or according to the subject's own decision. Previously to the movement the ongoing EEG/MEG activity shows characteristic changes, namely either decreases or increases of power in specific frequency components as described above: ERD of μ oscillations appear before a movement of a finger, over the corresponding cortical area; this is followed by a robust rebound β ERS; just before the movement a burst of γ activity can be observed, although this may be difficult to detect at the scalp since it is very localized (Pfurtscheller and Lopes da Silva, 1999; Pfurtscheller et al., 1993). These findings obtained by means of scalp recordings have been substantiated by subdural electrocorticography (ECoG) using grids placed over the corresponding cortical areas (Crone et al., 1998a, 1998b).

Interestingly, these dynamic changes of ongoing EEG/MEG rhythmic activities strongly related to specific movements, e.g., of hands or feet, occur also if the subject just imagines the movement, without executing it, which makes these signals good candidates to operate brain-computer interfaces (BCIs) (for review, see Birbaumer and Cohen, 2007).

6. EEG/MEG: Some Novel Perspectives of the Application of Brain Oscillations in Neuropsychiatric Disorders

A timely question is whether EEG/MEG oscillations may provide biomarkers for diagnostic purpose in neuropsychiatric disorders. A general aspect that pervades this field is that many of these disorders share a common feature, i.e., they are determined by disturbances of the balance between excitation-inhibition (E/I) in neuronal networks. Recently, the hypothesis that such disturbances may be a common feature of neuropsychiatric disorders, such as schizophrenia and autism, has been put forward by Uhlhaas and Singer (2012), supported by experimental evidence of abnormal cortical γ oscillations in these neuropsychiatric disorders and also in some animal models with behavioral disturbances (Yizhar et al., 2011). Also, in the field of epilepsy, HFOs, which are associated with changes in E/I balance, have received much attention recently as being possible biomarkers of epileptogenic brain tissue. Another neuropsychiatric condition in which specific changes in EEG/MEG oscillations have been shown to be associated with behavioral symptoms is the attention-deficit hyperactivity disorder (ADHD). In this case, the pathophysiological features underlying the core symptomatology appear to be mainly related to disturbed functional connectivity between brain systems involved in attentional control.

6.1. Epilepsy: Are High-Frequency Oscillations Biomarkers?

A specific question is to what extent HFOs should be considered physiological or pathological phenomena and thus possible biomarkers of epilepsy. Seminal descriptions of HFOs were made in

the hippocampus (Buzsáki et al., 1992), namely short transient oscillations named “ripples” and “fast ripples” (90 Hz < ripples < 200 Hz < fast ripples); bursts of ripple oscillations were found in the hippocampus of epileptic rats and subsequently in the temporal cortex of epileptic patients (Bragin et al., 1999a, 1999b; Le Van Quyen et al., 2010).

The basic physiology of these HFOs is discussed in recent reviews (Buzsáki and Lopes da Silva, 2012; Jefferys et al., 2012). A current argument is how to distinguish “normal ripples,” i.e., ripples occurring in the normal brain and “pathological ripples” of the epileptic brain. A persuasive indication that HFOs may be biomarkers of epileptogenic tissue has been obtained in epileptic patients carrying indwelling EEG electrodes, who are candidates for a surgical removal of epileptogenic tissue. These studies revealed that surgical removal of brain tissue where HFOs are present is related to a favorable outcome of the resection, while less positive outcomes were noticed in those cases in which sites displaying HFOs were not completely removed (for a comprehensive review, see Jacobs et al., 2012).

Whether interictal HFOs can be reliably recorded at the scalp is a matter of current investigation. The differentiation in scalp EEG of interictal HFOs generated in the brain and EMG activity is challenging but appears possible. This differentiation is easier in EEG recordings made during sleep, since in this condition there is less EMG activity (Andrade-Valença et al., 2012).

The identification of HFOs as possible biomarkers of epileptogenic tissue has opened novel ways for the study of the pathophysiology of epilepsies in human with possible clinical applications.

6.2. Neuropsychiatric Disorders—Schizophrenia and Autism: Can EEG/MEG Make a Contribution?

Given the hypothesis that γ oscillations play an important role in the communication between different neuronal networks in the brain, an exciting challenge is to find out whether these oscillatory phenomena may be relevant to better understand the pathophysiology underlying some neuropsychiatric disorders. In this respect, two neuropsychiatric disorders are the main focus of attention: schizophrenia and autism spectrum disorders (ASDs).

With respect to schizophrenia, Nakazawa et al. (2012) and Carlén et al. (2012) pointed out the existence of a link between NMDA receptors, parvalbumine (PV)-GABAergic interneurons, γ oscillations, and schizophrenia-like cognitive impairments in animal models of the disorder. The hypothesis is that a disruption of γ oscillations impairs the functional connectivity within brain workspaces responsible for the cognitive impairments. The recent paper of Grützner et al. (2013) gives support to this hypothesis. These authors recorded MEG in 16 schizophrenic patients (although medicated) and in a matched control group, while the subjects were identifying “Mooney faces,” a task similar to that used by Rodriguez et al. (1999) mentioned above (5.1.3). In addition to showing a poorer performance in the detection of the faces, the patients also displayed a reduction of power in the γ band (60–120 Hz). This suggests that it may be rewarding to investigate the dynamics of γ -band oscillations in relation to specific cognitive deficits in schizophrenia.

With respect to ASDs, Khan et al. (2013) investigated subjects with ASD, using MEG, while these were asked to identify faces and houses. These authors focused on the coupling between

the phase of α oscillations and the amplitude of γ oscillations and estimated measures of local and long-range functional connectivity. The latter was reduced in the ASD subjects when these identified faces compared to control subjects, namely between the fusiform face area (FFA) and distant cortical areas involving the cuneus, infrafrontal gyrus, and anterior cingulate cortex. Briefly, although the diagnosis of ASD is a complex issue, these EEG/MEG investigations may open up new lines of inquiry.

6.3. Neuropsychiatric Disorders—ADHD: Can EEG/MEG Put in Evidence Signs of Inattention in the Brain?

There are several EEG studies carried out with the aim of describing neurophysiological profiles that would be characteristic of patients with ADHD but mainly in a steady state with the emphasis on diagnostics (Loo and Makeig, 2012). A conclusion of these studies is that these patients display an increased frontocentral θ to β power ratio during rest; the significance of this observation, however, remains unclear. As reviewed by Ogrim et al. (2012), the finding of increased θ/β ratio in ADHD is not a consistent finding. In recent years, however, the accent has moved to dynamic studies in which patients are investigated while performing tasks that put in evidence behavioral features characteristic of ADHD patients, in particular deficits in attentional processes that belong to the core symptomatology of this condition.

In normally developing children where subjects have to pay attention to a visual cue signaling the appearance of a visual stimulus, the latter is associated with a decrease of α EEG power over posterior head regions. This is not the case in ADHD patients of the same age group; furthermore, ADHD patients are slower in the performance of the task (Mazaheri et al., 2010). Along the same line, an MEG study in adults with ADHD, who were investigated during a visuospatial attention task, showed the inability of the patients to display lateralized α power decreases when visual cues were presented to one side of the visual field (ter Huurne et al., 2013). These investigations strongly indicate that in order to make significant progress in this field, it is necessary to carry out dynamic studies of EEG/MEG signals directly associated with the performance of well-defined cognitive tasks.

7. Concluding Remarks

In the last two decades, a considerable amount of experimental evidence was gathered that supports the notion that EEG/MEG signals can provide relevant insights into dynamic brain processes responsible for specific cognitive functions. We may distinguish three main functional roles of brain oscillations: (1) coding specific information, (2) setting and modulating brain attentional states, and (3) assuring the communication between neuronal populations such that specific dynamic workspaces may be created.

This perspective on brain functions is essentially dynamic and nonphenological. The critical issue is not simply to localize cognitive functions to some site in the brain but to find out the patterns of dynamic interaction between different brain systems underlying a cognitive process; indeed, to unravel these processes it is essential to understand the dynamics of the workspaces that constitute the material core of any cognitive process. For instance, a given conscious perception does not

depend exclusively on the activation of a well-localized cortical area, but it emerges from the dynamic interaction between several neuronal populations. This process includes intertwined changes of neuronal activities that enable information processing to take place by (1) the process of focal attention and suppression of distracters (as displayed by the suppression and the enhancement of α oscillations, respectively), and (2) the emergence of information carriers, as, for example, in the form of packets of γ oscillations that entrain neighboring networks and can be broadcast to distant populations, particularly nested with θ oscillations, by feedforward and recurrent connections. To grasp these dynamic cognitive processes that evolve at high speed, in a few tens of milliseconds, the fine time resolution of EEG/MEG is invaluable, and powerful analytical methods to estimate functional and effective connectivity are indispensable. The shortcoming of the limited spatial resolution of these signals can be, to some extent, compensated by advanced spatial dynamical mapping techniques. Methodologies to perform better integration of EEG/MEG with fMRI are being actively developed and are opening up novel exciting perspectives for the study of the dynamics of brain functions with respect to cognitive processes.

In short, brain oscillations should be considered as neural mechanisms underlying cognitive processes and not as simple correlates.

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