

# ANALELE UNIVERSITĂȚII BUCUREȘTI

## FILOSOFIE

2011

### Volumul II

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# THE SYNCHRONY OR TEMPORAL CODING THEORY (TEMPORAL BINDING)

MIHAI VACARIU, GABRIEL VACARIU\*

## *Abstract*

The binding problem remains one of the most important and unsolved problems in cognitive science. One of the proposed solutions, which is probably the most accepted in the scientific community, involves the synchronized oscillations. According to this theory, the integration of the brain areas responsible for various features, such as color or spatial dimension of a perceived object, is the outcome of the synchronized oscillations of the neurons. Electroencephalogram (EEG) results show us that different frequency bands are correlated with particular mental states. However, after presenting in detail this approach, we try to show that it still encounters serious obstacles to be considered the definitive solution for the binding problem.

**Keywords:** oscillations, frequency bands, gamma range, EEG, binding problem.

## **1. The Binding Problem: a Brief Description**

In the last decades, there has been a significant progress in the area of cognitive science and related fields such as neuroscience and cognitive neuroscience. Particularly, the advances in functional neuroimaging technology have offered to scientists the possibility to understand better the relationship between the activity in certain brain areas and certain explicit mental functions. Nevertheless, one of the most important issues in cognitive science, the binding problem (and its related problem – localization), has not yet been solved. It is still difficult to approach and further to understand the relationship between the function of the mind and the brain processes<sup>1</sup>. Several definitions of the notion of binding have been proposed, but many of them refer, in one or another way, to the modality of how specific activated neural patterns of neurons are *correlated* with certain features or properties of an object (like color, size,

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\* University of Bucharest

<sup>1</sup> ROSKIES (1999) considers the binding problem to be “one of the most puzzling and fascinating issues that the brain and cognitive sciences have ever faced”; TREISMAN (1996) points out that a solution to the binding problem may also throw light on the problem of the nature of conscious awareness (in VELIK 2010, p. 994).

motion, orientation) and how, in the end, they generate the mental unity of that object. Researchers such as Velik (2010), Plate (2007), Robertson (2003), Feldman (2010), Flevaris, Bentin and Lynn (2010), Humphreys et al. (2002) bring into discussion various forms of binding: spatial (location<sup>2</sup>) or temporal, conscious or unconscious, visual (linking together color, form, motion, size, and location of a perceptual object or binding various perceptual objects), auditory, cognitive (explains how a concept is connected to a percept), binding in language understanding, in reasoning, cross-modal binding, sensory-motor binding, memory binding and the causes of an unified conscious experience. However, there is something else that we always need to take into account (that is to use) when we analyze, in any way, the binding problem: that we need a very specific framework to situate the entire analyze in order to find the right solutions. The same framework should be suitable for investigating the mind-body problem too (and the more specific problem of representation). If we look carefully to the history of these problems, we can notice that one single framework has always been used for both problems. This framework is based on the idea that we live in a single unified world in which we can “observe” and “correlate” various entities of different nature, such as activated patterns of neurons, mental states, and so on. Within this framework, the binding problem still remains unsolved and it seems to be the main challenge for cognitive (neuro)scientists. Velik writes that the binding mechanism is “almost everywhere in the brain and in all processing levels” (Velik, 2010, p. 994). Out of the proposed solutions to the problem, the idea of “synchronized oscillations” in neuronal networks seems to be most accepted today, so we present it in detail below. In the last part of the essay, we try to show the main problems of this approach.

## 2. “Synchronized Oscillations” – a General Framework

An alternative for the superposition problem of population coding and the combinatorial problem of convergent hierarchical coding is the temporal binding hypothesis initiated and developed by C. Legendy (1970), P. Milner (1974) and C. von der Malsburg (1981) (Von der Malsburg, 1999). The binding problem is realized through the “synchronous neuronal oscillations” under different frequencies. Using EEG<sup>3</sup> or MEG, electrophysiological signals are obtained at the scalp level, signals that mirror the “synchronization of weak

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<sup>2</sup> Treisman specify that objects and location seem to be separately coded in dorsal and ventral pathways “raising what may be the most basic binding problem: linking ‘what’ to ‘where’” (TREISMAN 1996).

<sup>3</sup> “Intracranial EEG (iEEG) has a far better signal-to-noise ratio than scalp EEG, since it is recorded from the brain itself. iEEG voltages typically are measured in millivolts; scalp EEG is measured in microvolts.” (BAARS and GAGE 2010, p. 262).

synaptic currents across a large number of neurons: scalp signals therefore necessarily reflect *synchronized* neural activity” (Tallon-Baudry 2009, p. 322) or “rhythmic modulation of discharge activity (neuronal oscillations)”. The coupling of neurons through synchronization depend on the adjusting the phase relationship or frequency of the cells from that neuronal group. The phase of an oscillation provides the window for processing information. Inputs in “good phase” of the ongoing oscillation are selected, inputs in “bad phase” are suppressed (Moser *et al.* 2010, p. 199). There is the hypothesis that the synchronization between the different areas is achieved through the zero-phase lag between the same frequent-oscillatory activities.

When two brain regions fire in synchrony with a lag time, the term phase locking is more accurate than synchrony. Sound waves echoing in a canyon are phase locked but not synchronous, because they echo back and forth with a brief lag time. Because neurons also take time to send their axonal spikes, there is a lag time in echoing among related brain regions, leading to phase locking rather than synchrony. Both synchrony and phase locking are commonly observed in the brain.<sup>4</sup> (Baars and Gage 2010, p. 252)

Experiment results showed that zero-phase lag synchronization can occur over local brain areas or large distances even if there are great conduction delays of pathways that connect the synchronized neural groups. (Moser *et al.* 2010, p. 205)

A power increase in a given frequency band at an electrode or MEG sensor is thus considered as measure of local oscillatory synchrony, probably generated through local, within-area neural interactions. Long-range oscillatory synchrony, thought to arise from between-area recurrent feed-forward/feed-back loops, is best characterized by phase synchronization (20), although some care has to be taken when using this measure at the scalp level (...). (Tallon-Baudry 2009, p. 322)

According to Baars and Gage (2010, p. 107), the main frequency bands and their features are roughly these ones: delta wave (less than 4 Hz) – the slowest wave with the greatest amplitude, typically for deep sleep (unconscious) states. It is known that if our awareness of the external world decreases, delta wave increases. Theta wave (3.5 to 7.5 Hz) – available for sleep states and meditation or, creating communications between hippocampus and cortex, it is involved in short term memory and memory retrieval tasks; alpha wave (7.5 to 13 Hz) arises in relaxation moments (when the eyes are close; if the eyes are open, alpha wave is attenuated); beta wave (13-26 Hz) – irregular, low voltage available for waking conscious states, symmetrically distributed in both hemispheres (most evident in

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<sup>4</sup> “Sometimes perfect synchrony is not attainable, so that there is a brief time lag between the peak of the wave in one place (like the hippocampus) and another place (like the frontal lobe). In those cases, the better term is phase locking or phase coherence, a little bit like a syncopated ‘off-beat’ rhythm in music. It is synchrony with a time lag.” (BAARS and GAGE 2010, p. 261).

the frontal area); gamma wave (26-70 Hz<sup>5</sup>, centered around 40 Hz) – available for conscious states (conscious perceptions and other cognitive states) and in REM dreams (rapid eyes movement sleep) creating communications between cortex and subcortical areas.

It is important to note that EEG technique captures only the surface waves, while under these there are other important wave interactions (locked in synchrony with each other, phase-locked, transiently coordinated, cross-frequency coupling) and they are within different ranges (recent findings indicate that they range from 0.01 to 1000 Hz) (Baars and Gage 2010, p. 254). The research in the field evolves rapidly and these results might indeed be just approximations. Baars warns us in this respect: “*Keep in mind that brain rhythms are a moving target, as new evidence appears with remarkable rapidity*” (Baars and Gage 2010, p. 261) According to Singer, segmentation up to 90 Hz, for large distances is beta and gamma frequencies between 30-60 Hz, consciousness is associated with phase locking of gamma oscillations across widely distributed cortical areas, while unconscious processes are associated with local gamma oscillations (Singer 2010, p. 165 or 2009, p. 49) Singer, among others, mentions that the firing rate (discharge rate) is characteristic for particular features, while synchronization correlates these features (Singer 2010, p. 164; see also Singer 2009).

Moser and his colleagues suggest that the phase of oscillations (relative timing) is used for coding. The responses of synchronized cell populations to the strong excitatory inputs on the rising phase of the oscillation are earlier comparing with the responses to the weak inputs. They claim that the “intensity can be encoded in the time of spiking relative to the oscillation phase. This is a convenient way of coding since the latency of first spikes already contains all information about the amplitude of the driving input”. (Moser *et al.* 2010, p. 199) Oscillations are necessary for synchronizing the spikes for propagating them in sparsely networks, spikes timing “has to be adjusted with high precision for the definition of relations in learning processes such as spike timing-dependent plasticity” and the information about input amplitude or the relationships between distributed processes is found in timing relations between spikes or between spikes and the phase of a population oscillation (Moser *et al.* 2010, p. 200).

An oscillatory modulation of membrane potential, such as occurs in oscillating cell assemblies, confines spiking to the rising slope of the depolarizing phase. Thus, spikes emitted by networks engaged in synchronous oscillations become synchronized. The temporal precision of this synchronization increases with oscillation frequency. In the case of gamma oscillations, output spikes can be synchronized with a precision in the range of a few milliseconds. Because of the coincidence sensitivity of neurons, this synchronization greatly increases the impact that the output of synchronized cell assemblies has on subsequent target neurons. (Moser *et al.*, p. 199)

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<sup>5</sup> The actual taxonomy of gamma band is low band (30-60 Hz) and high band (60-120 Hz).

One of the most exciting issue in cognitive neuroscience today regards the integration of different neural patterns of activation that are correlated with particular mental functions (the correspondent issue in the visual binding problem involves the features of a perceived object). It is usually considered that the activity of certain neural patterns responsible for the presence of a particular mental (perceptual) feature, while grouping all the features of one (perceived) entity are due to synchronization processes. Such an integration is correlated with the unity of consciousness/mind/subjectivity (the binding problem is the unity of perceptual scene/object).

A related area of research which has to do with the *dynamic coordination* in the brain/mind has been recently approached by various researchers in a new book *Dynamic Coordination in the Brain From Neurons to Mind*, edited by Philips, von der Malsburg, Singer (2010). The main interest regards the coordinated interactions “that produce coherent and relevant overall patterns of activity, while preserving the essential individual identities and functions of the activities coordinated”.<sup>6</sup> (Philips *et. al.*, 2010, p. 1) The main problem then remains the combination of the *global* information (“relational Gestalt organization”) with the *local* information in the brain (information that is correlated with local and global mental functions/states). There are two main mechanisms for this coordination: by gain modulation (synaptic gain changes, activity-dependent gating – “when dendritic segments are switched off by shunting inhibition” – the activation of synapses along a dendrite is change, etc.) or by synchronization of oscillation patterns (Moser *et al.* 2010, pp. 198-9). However, the gain is not that suitable for the speed and flexibility of cognitive processes. Therefore, the oscillatory synchrony approach is probably a better alternative to the issue and this is the main reason it is more popular among scientists. Among the groups of neurons, the frequency and phase adjustments are necessary for the selective routing activity and the dynamic gating of interactions between neural areas. Moreover, through the same mechanisms, the groups of neurons can be connected into coupled assemblies or segregated into functionally subgroups. The oscillations with these mechanisms “could serve three complementary functions: gain control, selective and flexible routing of information between neuronal groups, and formation of coherent representations.” (Melloni and Singer 2010, p. 20) Neural oscillations determine the relationships (“coordination”) among distributed neurons through synchronization. It is largely accepted the idea that the oscillatory synchrony is not the only mechanism for coordination in the brain. All these mechanisms are in fact complementary.

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<sup>6</sup> Coordination is quite similar with binding. For VON DER MALSBURG coordination “is the ability to create internal scenes that capture the reality of environment”. (2010, p. 155). According to the editors of the book, neural synchrony oscillations and vector coding are two distinct and complementary processes that can be correlated with various cognitive processes.

Singer claims that the features of perceptual objects are encoded at subcortical levels, while the objects as a whole and the relationships among these features and objects with their environment are encoded by intracortical neuronal connections and “iterative recombination of feed-forward connections from lower- to higher-order neurons” (Singer 2010, p. 159). The brain has obviously a hierarchical structure, with systems and subsystems, neural codes and oscillations, feed-forward and feed-back signals and other entities and processes. However, all these elements have to be correlated somehow with the mental functions and the overall unity any individual. The problem is that the neural patterns (modalities or subsystems) have to be *reliable* (“neural codes must code for the same thing when used at different times and in different contexts”) and *flexible* (codes must be used in different ways at different times and in different contexts” (Philips, von der Malsburg and Singer 2010, p. 2). The relational information encoded by different neural areas under dynamic coordination framework has to change in a context-, task, and goal-dependent way (Moser *et al.* 2010, p. 194).

Notions such as coding and coordinating interactions are applied at each level of neuronal processing from single-unit to population coding that form the hierarchical structure of the brain. The frequency bands are the most attractive tool for grasping the neural integration. Among the first who introduced this approach is von der Malsburg with his “binding-by-synchrony” hypothesis. However, we have to integrate even the frequency bands before to talk about the binding problem. For any perceptual scene, we need not some “vectors of activity” able to grasp all the entities and their relations from that scene, but “dynamical graphs” that change more rapidly (Moser *et al.* 2010, p. 204). Numerous cognitive neuroscientists are working hard to explain which neural states are responsible for each perceptual feature (segmentation/localization) and how of all these features get integrated in a single perceptual scene (the binding problem). For acquiring a mental representation of the perceived object, a temporal correlation or a synchronization of the firing neurons occurs among the neuronal patterns involved. It is plausible to believe that different synchronous neuronal oscillations are correlated with mental features.<sup>7</sup> In this context, it seems that we cannot talk about the binding problem without taking into account the segmentation/localization problem.

### **3. Frequency Bands: in What Neural Areas Are Active; What Cognitive Functions Are Correlated with Each Band?**

Tallon-Baudry reminds us that in the past, each frequency band was associated with a cognitive function or state: delta waves were associated with

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<sup>7</sup> For the perception of a single, simple object, more than 36 neuronal areas are activated in occipital, temporal and parietal lobes. It seems quite difficult, but not impossible, to identify the frequencies bands responsible for the integration of so many neuronal areas in different lobes.

sleep, theta<sup>8</sup> band with memory, alpha wave with vigilance fluctuations (more recently, with mental imagery and other mental processes – Baars and Gage 2010, p. 270), beta and gamma ranges with active awake stages and later with feature binding, attention, and memory (Tallon-Baudry 2010, p. 239 or 2009). Quoting different authors, she offers some examples of actual such associations: gamma range (plus alpha range) for the binding perceptual features, from theta to gamma frequency bands (but also alpha frequency) for various attentional tasks or for episodic memory encoding and retrieval, gamma and beta range for visual short-term memory (pp. 239-40 or 2009, p. 326). Singer also presents functions which are associated with synchronization: binding (see below), attention (gamma and beta frequency bands) stimulus selection, and consciousness. Results in the last decade indicate that subdivisions of some frequency bands (for instance, gamma sub-bands) correspond to particular cognitive functions and vice-versa. Some researchers want to prove that the interactions within large-scale cortical areas (i.e., communication among various cortical areas) are produced by long-range synchronization of oscillatory signals. Singer specifies that synchronization among distant neuronal areas occur at oscillations in the theta or beta frequency range; synchronization among local groups of neurons is produced by gamma oscillations. As we mentioned above, oscillations in different frequency bands can coexist and exhibit complex phase relations (Roopun *et al.* 2008). We should consider then the “nested relations” hypothesis (Singer 2010, Moser *et al.* 2010) necessary for encoding the compositionality (for instance, the representation of composite perceptual objects and movement trajectories)<sup>9</sup>. More recently, Hipp *et al.* (2011) argue that beta-band synchronization (20 Hz) work in fronto-parieto-occipital areas, while gamma-band synchronization (80 Hz) in centro-temporal areas. Hipp and colleagues analyze the results of EEG recordings in human subjects that report the alternation of a perceptual ambiguity (audiovisual stimulus). Regarding the beta-band synchronization they show that the

intrinsic fluctuations of synchrony may predict<sup>10</sup> the subjects’ alternating perception of the constant physical stimulus. Indeed, we found that beta-synchrony was not only enhanced during stimulus processing but also predicted the subjects’ percept of the stimulus. (Hipp *et al.* 2011, p. 389)

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<sup>8</sup> Theta (also alpha) seems “to ‘carry’ gamma oscillations in much the way an AM radio frequency carries a voice signal”. It plays a role in episodic memory being involved in actions of frontal lobe and hippocampus.

<sup>9</sup> “So-called nested oscillations attracted a great deal of interest because of an influential model of memory storage that would account for the limits of human memory capacity by an interplay between theta and gamma oscillations (LISMAN and IDIART 1995), and there is growing evidence in humans for such theta/gamma relationships (CANOLTY *et al.* 2006; SAUSENG *et al.* 2008).” (TALLON-BAUDRY 2010, p. 243).

<sup>10</sup> “The role of oscillatory synchrony in top-down attention appears also before stimulus onset, when subjects anticipate the appearance of the stimulus: pre-stimulus gamma oscillations successfully

Recent experiments show that the temporal structure of activity patterns indicates the states of “expectancy” or anticipation” before the appearance of stimuli (Engel *et al.*, 2001 in Velik 2010, p. 999). It seems that the fluctuations of large-scale beta-synchrony determined the perceptual interpretation of stimulus (p. 389). Hipp proposes that the beta-band synchronization is the mechanism that mediates large-scale interactions among frontal, parietal and extrastriate areas. The gamma-band synchronization is implicated in the subjects’ percept of the ambiguous stimulus and it is directly linked to the cross-modal integration of auditory and visual information.” (Hipp *et al.* 2011, p. 389, 390) The gamma-band synchronization includes central (sensorimotor and premotor regions) and temporal areas involved in multisensory processing. Premotor regions are involved in auditory, visual, and somato-sensory stimuli, while temporal regions in cross-modal integration of audiovisual stimuli<sup>11</sup> (Hipp *et al.* 2011, p. 392). Mentioning the work of some cognitive neuroscientists, Tallon-Baudry indicates disparate results regarding these correlations: occipital, temporal, parietal and frontal regions or a focal activation, confined to the occipital pole. The problem is that MEG and EEG provide a different image of the visually induced oscillations: “while EEG data reveal a short-lived burst of oscillatory synchrony between 30 and 60 Hz and 200 and 300 ms, MEG studies consistently report sustained oscillations at higher frequencies.” (Tallon-Baudry 2009, pp. 322-3) The results show that visual stimulus produce gamma oscillations at different areas and different frequencies (p. 324).

Fries emphasizes three main reasons gamma-band synchronization is so important in cortical computation: this frequency band (30-100 Hz) is involved in many brain regions (visual, auditory, somato-sensory, motor, parietal cortex and outside the neocortex, the hippocampus; we can identify it at various species (from insects to humans); it is correlated with many human cognitive activities (sensory stimulation, attentional selection, working memory maintenance and so on. (Fries *et al.* 2009, p. 309) Other experiments suggest that visual attention is correlated with increases in coherence between local field potentials from the frontal and parietal cortex (Buschman and Miller 2007, 2009 in Moser *et al.* 2010, p. 200). Theta oscillations seem to have a role in local hippocampal functions and in long-range coordination between the hippocampus and neocortex (Baars and Gage 2010, p. 259). Tallon-Baudry strongly emphasize that there is no strict correspondence between

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predict the speed of reaction times (55-57), are modulated by the degree of predictability of the stimulus (57-60) or the information content of the warning cue (61, 62). Oscillatory synchrony in the gamma range thus appears as an efficient mechanism to establish a neural state facilitating the processing of forthcoming stimuli – in other words, anticipatory attention.” (TALLON-BAUDRY 2009, p. 324).

<sup>11</sup> Interestingly for Hipp is that the experiments indicate a “surprising dissociation between local oscillatory activity and long-range synchronization”. (HIPPI *et al.* 2011, p. 392) Importantly for the main topic of this work, like many others, these authors indicate that the large-scale cortical synchronization are strongly related to the perceptual organization of sensory information. (p. 392).

a frequency band and a cognitive process<sup>12</sup> (p. 239 or 2009, p. 325). However, in spite of this extensive research on synchronized oscillations, it is still not clear whether we can correlate a frequency band with a particular cognitive function. Tallon-Baudry is even more explicit:

the functional role of oscillatory synchrony in distinct frequency bands may simply depend on the functional specialization of the area that generates these oscillations (Tallon-Baudry *et al.* 2005), much as the functional significance of ERPs depends on the areas that generate them. (Tallon-Baudry 2010, p. 240)

The correlation between a cognitive function and a frequency band depend on two sets of features: physiological needs (network's size and geometry, time, coding precision required, and metabolic costs for oscillations) and cognitive constraints (time, "chunks of processing", the number of cognitive function can be multiplexed) (Tallon-Baudry 2010, p. 241-2). Scheeringa and his team obtained some interesting results in respect to the relationships between BOLD signals and different frequency bands (alpha, beta and gamma powers)<sup>13</sup>. The main conclusion of their empirical results (simultaneously recorded EEG and BOLD while subjects engaged in a visual attention task) is that low-frequency (alpha and beta bands) neuronal synchronization are correlates negatively with BOLD signal changes, while high-frequency (high-gamma band) neuronal synchronization correlates positively with BOLD signal changes (Scheeringa *et al.* 2011).

All the above results regard mainly the issue of segmentation and they should bring some new insight on the more difficult problem of integration of different brain areas with variable frequency bands. Following different criteria, there are various alternatives for cross-frequency coupling, but three main interactions are co-variations in amplitude (the power of one frequency that increases can determine the increase or decrease of the power of another frequency), phase coupling between frequencies (it coupling an oscillation with  $n$  cycles to another with  $m$  cycles, i.e.,  $n:m$  phase synchrony)<sup>14</sup>, or phase-

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<sup>12</sup> "There is no doubt that gamma-band oscillations are influenced by stimulus low-level features in sensory regions (HALL *et al.* 2005; ADJAMIAN *et al.* 2008), but whether this still holds true for higher-level areas remains an open issue." (TALLON-BAUDRY 2010, p. 241) Moreover, we have to take into account that "the visible EEG waves are just the waves on top of the oscillatory lake. Underneath the irregular scalp EEG there are known to be synchronized rhythms." (BAARS and GAGE 2010, p. 270).

<sup>13</sup> Tallon-Baudry emphasizes that there is no event-related potential element correlated with gamma range for perceiving an object. Therefore, the neural properties reflected by induced gamma power synchronization and ERPs are different (TALLON-BAUDRY 2009, p. 322).

<sup>14</sup> "Cross-frequency phase coupling links alpha, beta and gamma oscillations in humans during mental calculation and in a working memory task." (PALVA, J. M., S. PALVA & K. KAILA 2005, in Tallon-Baudry 2009, p. 326). For a review regarding the role of gamma-band for attention and memory, see JENSEN *et al.* (2007).

amplitude coupling. The phase of an oscillation could influence the amplitude of another oscillation (Tallon-Baudry 2009, p. 326). There is the hypothesis that the faster waves (for instance, gamma range) may “multiplex” on slower waves (theta or alpha range) (VanRullen and Koch in Baars and Gage 2010, p. 255). In other words, theta oscillations (or even alpha), for instance, can group gamma band. Alpha band can group gamma oscillations in working memory (Palva and Palva 2007 in Baars and Gage 2010, p. 270). “Steriade (2006) has suggested that slow oscillations may generally work to group faster ones. Even the newly discovered ‘slow oscillations’ that range from 0.1 to the delta range may serve to group theta, alpha, beta, and gamma.” (Baars and Gage 2010, p. 269) The conjecture is that cross-frequency phase synchrony between alpha, beta, and gamma oscillations “coordinates the selection and maintenance of neuronal object representations during working memory, perception, and consciousness” (Palva and Palva 2007 in Baars and Gage 2010, p. 270). But, “we now have a number of separate sources of brain evidence showing coherent gamma bursts in association with conscious perceptual moments, paced by rhythms near theta or alpha.” (Baars and Gage 2010, p. 290)

It seems that our knowledge about oscillations is still contradictory. We mention He and Raichle (2009) who emphasize the difference between oscillation and fluctuation. They introduce the notion of “slow cortical potential” (SCP), a low-frequency end of field potentials ( $< 4$  Hz), that seems to be the best alternative for carrying out large-scale information integration in the brain. SCP is the neural activity correlated with consciousness. Nevertheless, they consider SCP being a kind of fluctuation and not oscillation. They classify the EEG results in three distinct groups: rhythmic, arrhythmic, and dysrhythmic.

The first two appear in normal subjects and refer to waves of approximately constant frequency and no stable rhythms, respectively. The latter refers to pathological rhythms in patient groups. Rhythmic EEG is further subdivided into frequency bands known as d, u, a, b and g, etc. The SCP frequency range does not normally contain any true rhythmic activity, except the “up-and down states” (...). The “up-and-down states” is a distinct phenomenon that can be easily differentiated from the SCP (...). Therefore SCP is a fluctuation rather than oscillation (B. J. He *et al.*, unpublished) (He and Raichle 2009, p. 303).

Inspired by the work of several researchers, the authors conclude that the SCP has a close correspondence to the fMRI signal and the synaptic activities at apical dendrites in superficial layers produce the SCP. More exactly, it is about the “long-lasting excitatory postsynaptic potentials (EPSPs) at these apical dendrites underlie negative-going surface recorded SCPs (...)” (p. 303). Introducing various experiments, He and Raichle conclude that “long-range intracortical and feedback cortico-cortical connections, as well as the nonspecific thalamic inputs, all contribute directly and significantly to the SCP.” (p. 305) They believe that it is possible the SCP to be a “more fundamental correlate of the fMRI signal than LFP

power is” (*idem*). Thus, the SCP is the best alternative for neural process that are correlated with consciousness since “(i) its slow time scale allows synchronization across long distance despite axonal conduction delays [15,44-46]; (ii) long-range intracortical and corticocortical connections terminate preferentially in superficial layers and thus contribute significantly to the SCP”. (*idem*) He and Raichle introduce experiments that show that many mental processes (attention, perception, volition) require the presence of the SCP.

#### 4. Gamma Range in Visual Cognition

All these results in neuroscience should have, in the end, an impact on the binding problem. As an example, we present the role of gamma range in human visual cognition. Gamma band is between 30-120 Hz, being low range (30-60) and high range (60-120) with various cognitive functions. In the late 1980s and early 1990, von der Malsburg, Singer, Engel and Gray were the firsts who showed that the gamma band frequency is related to the visual binding (Tallon-Baudry 2009 or Fries 2005). It has been later discovered that this range is involved in many other cognitive functions related with attention, memory or awareness.

Induced gamma oscillations are thus not related to a single cognitive function, and are probably better understood in terms of a population mechanism taking advantage of the neuron's fine temporal tuning: the 10-30 ms time precision imposed by gamma-band rhythms could favor the selective transmission of synchronized information (attention) and foster synaptic plasticity (memory). Besides, gamma oscillatory synchrony also seems related to the emergence of visual awareness. The recent discovery that gamma oscillations could appear simultaneously in distinct areas at distinct frequencies and with different functional correlates further suggests the existence of a flexible multiplexing schema, integrating frequency bands within the gamma range but also at lower frequency bands. (Tallon-Baudry 2009, p. 321; also p. 326)

The best solution to the perceptual binding problem seems to be the synchronized oscillations alternative, a process that is involved probable in all visual levels (from retina to the highest cortical area) solving both segmentation and integration processes (Singer 2010, p. 163; about gamma-band and conscious perception, see also Singer 2009).

In all cases, synchronization probability reflects some of the Gestalt criteria that are used for scene segmentation and perceptual grouping. In the retina, ganglion cell responses synchronize with millisecond precision if evoked by continuous contours (Neuenschwander and Singer 1996). This synchronization is associated with high frequency oscillations (up to 90 Hz) and is based on horizontal interactions within the network of coupled amacrine cells. In the visual cortex, synchrony is often associated, especially when it is observed over larger distances, with an oscillatory pattern of spike discharges in the beta and gamma frequency range (30-60 Hz). (Singer 2010, p. 163)

The perception of a meaningful object is correlated with a burst of induced gamma oscillatory synchrony over occipital electrodes between 200 and 300 ms. With new methods of investigations, segmentations and object identification take place within less than 200 ms, grouping operations happening in 10 to 20 ms (Thorpe et al. 1996; VanRullen and Thorpe 2001 in Singer 2010, p. 163). “When the perceived object spans the vertical meridian, gamma oscillations in both hemispheres become phase-locked (...). The latency of this burst of oscillations correlates with object recognition delays (...).” (Tallon-Baudry 2009, p. 322) Among binding features, gamma oscillations are involved in spatial, feature-based and object-based attention (Tallon-Baudry 2009, p. 324). Frégnac et al (2010) analyze the notion of dynamic coordination applied certain neural processes correlated with non-attentional perception and in respect to the relationship between the whole and the parts, that is segmentation and integration (binding) regarding the sensory stimulus correlated with neural processes/states, the authors concluded that

to a certain extent, both in invertebrate ganglia and the vertebrate brain, the dogma of separability between intrinsic and extrinsic factors in the control of cellular excitability is doomed to fail. Thus, the “whole” cannot be the sum of the “parts,” and segmentation does not always coexist with perceptual binding. (Frégnac *et al.* 2010, p. 172)

Using the results of in the area of perception (visual illusions), Frégnac and colleagues try to show that the Gestalt rule is correct: the whole *precedes* the detection of the parts in time. They show that within the dynamic coordination, the “dynamical agent” could be an internal supervisor embedded in the network, the sensory drive or an external prior. Using binocular rivalry in the cat, Engel and Singer explore the role of gamma oscillations in comparing conscious versus unconscious stimulus processing in the visual cortex with identical physical input to the both eyes. In more detail, “in the cat’s cortex, the dominant (conscious) eye demonstrated gamma synchrony locked to the ‘conscious eye’, whereas the nondominant (unconscious) eye showed no synchrony.”<sup>15</sup> (in Baars

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<sup>15</sup> “Direct evidence for an attention related facilitation of synchronization has been obtained from cats that had been trained to perform a visually triggered motor response (...). Simultaneous recordings from visual, association, somatosensory and motor areas revealed that the cortical areas involved in the execution of the task synchronized their activity, predominantly with zero phase-lag, as soon as the animals prepared themselves for the task and focused their attention on the relevant stimulus. Immediately after the appearance of the visual stimulus, synchronization increased further over the recorded areas, and these coordinated activation patterns were maintained until the task was completed. However, once the reward was available and the animals engaged in consummatory behaviour, these coherent patterns collapsed and gave way to low frequency oscillatory activity that did not exhibit any consistent phase relations. This close correspondence between the execution of an attention demanding visuo-motor performance and the occurrence of zero phase-lag synchrony suggests a functional role of the temporal patterning in the large scale coordination of cortical activity.” (SINGER 2009, p. 47).

and Gage 2010, p. 265). An interesting hypothesis is advanced by Singer who claims that in the case of binocular rivalry, the two patterns that are perceived in alternation necessitate a mechanism “which selects in alternation the signals arriving from the two eyes for access to conscious processing” (Singer 2009, p. 48).

### 5. The Main Difficulties with the Temporal Coding Hypothesis

In spite of some advances regarding the synchrony oscillations, it is still unclear their role in binding. The general hypothesis has to do more with how binding is signaled and not how binding is computed, as Velik remarks (Velik 2010, p. 997), and synchronization cannot be an alternative for the enduring trait of representation of an object (LaRock 2010, p. 455 or 457). The synchrony oscillatory hypothesis is flexible regarding the long-term memory, but the problem is that “even features that are very likely to co-occur would need to be bound anew every time they are encountered. Thus this kind of binding would be economical in terms of cognitive structure but wasteful in terms of processing time.” (Hommel and Colzato 2009 in Veliko 2010, p. 998). The synchrony oscillatory does not explain the spatial structure necessary for binding the features<sup>16</sup> (LaRock 2007, p. 801). Also, Van der Velde and de Kamps accentuate the idea that synchronization does not solve the productivity in the case of binding (Van der Velde and de Kamps 2006, p. 41). They indicate that for the binding constituents in combinatorial structures, synchrony detectors will be missing for novel such structures (Van der Velde and de Kamps 2006, p. 41). Some very recent experiments on visual mechanism of monkeys show that the synchronization does not depend on the binding problem, but only on the selectivity of finding the “border-ownership” of an object (Yi Dong et al. 2008). That is to say, the synchronization process takes place for the detection of an object’s border and not for the binding of the object’s features. Moreover, Robertson emphasizes that empirical evidence from neuropsychology indicate that preattentive binding can influence performance (Robertson 2003, 2005), while Humphreys et al. indicate that perceptual performance is facilitated by unconscious binding<sup>17</sup> (Humphreys *et al.* 2002, p. 363).

### 6. Conclusion

As it is the case with all the other solutions to the binding problem, the synchronized oscillations paradigm still encounters fundamental difficulties. In

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<sup>16</sup> It is suggested that parietal lobes are necessary for spatial feature (ROBERTSON 2003).

<sup>17</sup> For more arguments against the idea that synchronized oscillations hypothesis can explain the binding problem see VELICK (2010).

order to solve the binding problem, we have to bring somehow into the equation the issue of the unity of self (and of consciousness) and, also, the more essential issue of the relationship between mental states (representations) and the self. In our opinion, it has no sense to try to establish a direct relationship between mental entities and neural patterns in the brain as they belong to epistemologically different worlds (as we call them<sup>18</sup>). From such a perspective, it would be beyond any framework of understanding the attempt to explain the unity of an entity or object, for example a table, through the role of the micro-forces among the microparticles which “compose” that table. The unity of that object does not exist at the “level” of microparticles (which includes the interactions between these microparticles). Entities such as the microparticles together with their interactions belong to a different framework, while the object in discussion, a “table”, belongs to another framework, that is, to an epistemological different world. Following this analogy, we claim that the binding problem is in itself a pseudo-problem, as it is meaningless to explain the unity of a mental state (for example, a mental representation) through entities and processes that take place in the brain. They are different entities which belong to epistemologically different worlds. Thus, exactly like the more general issue, the “mind-body problem”, the binding problem seems to be impossible to be solved within the current general framework, in which it is considered and accepted that we can explain processes and entities through other processes and entities which are actually situated in different “worlds”<sup>19</sup>.

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<sup>18</sup> From an EDWs perspective, “levels” is a meaningless notion, since mind and brain belong to EDWs (See VACARIU 2005, 2008, 2011a and b, VACARIU and VACARIU 2010).

<sup>19</sup> For a detailed explanation of the “epistemologically different worlds” perspective see VACARIU (2009, 2011a, 2011b) and VACARIU and VACARIU (2010).

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