

Multiple Oscillations and Phase Locking in Human Gamma Responses: An Essay in Search of Eigenvalues

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ABSTRACT

This report describes a new strategy to analyze and interpret the fine structure of the human brain's gamma oscillations between the frequency ranges of 28 to 48 Hz. There are at least 3–4 phase/time-locked gamma responses within the 28–45-Hz frequency window. Late responses starting around 300 ms are probably responses that are conveyed over reticular formation, hippocampus, etc., whereas the early response in the primary occipital cortex O1 starting at 100 ms is most probably the direct response over the short pathway over lateral geniculate nucleus. Eigenvalues or nodes: It is remarkable that nodes or Eigenvalues are observed, despite the complexity of the pathways and the superposition of several oscillations. It appears that the event-related oscillations in the gamma band undergo an increasing frequency modulation. The time course in the first 200 ms has lower frequencies of approximately 28–30 Hz. With increasing time, the frequencies of these oscillations reach values of up to 46 Hz. The brain reacts within three-to-four frequency bands, depending on the modality of stimulation. In the context of quantum dynamics, the results are tentatively explained via the concept of eigenvalues.

Key Words: oscillation, phase locking, human gamma responses, eigenvalues

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1. Brain's Gamma Band Oscillations

The present report aims to introduce a new type of concept and analysis for brain oscillatory gamma responses, which will also serve as a pilot study for other frequency windows.

1.1 Evolution of research in the gamma band

Neuronal gamma-band oscillations, which can be recorded in many cortical and sub-cortical areas in the mammalian brain and in invertebrate ganglia, are evoked or induced by different stimuli or tasks. Many different gamma-band oscillatory processes are involved in diverse functions (Herrmann *et al.*,

2004). Further, there are several views related to the role of gamma activity in the communication processing of the brain. These results often lead to controversies.

The empirical background of the gamma band dates back to Adrian (1942), who reported that the application of odorous substances to the olfactory mucosa of the hedgehog induced trains of sinusoidal oscillations within the 30–60 Hz range. Studies on the 40-Hz oscillation have passed a total of seven phases, initiated by Adrian (1942) in the first phase. According to Lavin *et al.* (1959) and Hernandez Peon *et al.* (1960), 40-Hz activity was not restricted to olfactory stimuli but could be elicited by a wide range of other conditions.

The second phase took place between 1960 and 1980, and was characterized by the works of (Freeman (1975), Başar *et al.* (1975a, b and c) and Sheer (1976), in which a variety of

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functions were ascribed to gamma oscillations. Başar and Özesmi (1972) introduced the term ‘gamma-response’ to describe hippocampal gamma-range activity to external stimuli in cats. Enhanced gamma-activity was especially seen in structures that were able to spontaneously fire in this mode (‘gamma-resonance’). In addition, 40-Hz oscillatory responses were also observed in humans (Sheer, 1989; Başar *et al.*, 1976; Galambos *et al.*, 1981). Further studies found gamma-range activities associated with visual (Eckhorn *et al.*, 1988; Gray *et al.*, 1989) and olfactory (Freeman, 1975, 1979) sensation. For a comprehensive review, cf. Başar-Eroğlu *et al.* (1996b) and Başar (1999).

The third phase started with the work of Galambos *et al.* (1981). This work led to investigations concerning the sensory and cognitive correlates of the gamma oscillation primarily in humans.

The fourth phase is shaped with fundamental works of Eckhorn (1987) and Gray and Singer (1989), which led to investigations of 40-Hz at the cellular level.

The fifth phase is marked by the heterogeneity of approaches and techniques used to investigate gamma. During this fifth phase, at a workshop in New York, Galambos (1992) suggested a categorical system for classifying various findings of gamma-band activities measured in different species.

1. *Spontaneous* gamma activity, i.e., a fraction of the total EEG energy at any given moment without intentional stimulation (Başar and Özesmi, 1972; Sheer, 1976).
2. *Induced* gamma activity, i.e., activity initiated by, but not tightly coupled to a stimulus (Adrian, 1942; Freeman, 1975; Freeman and Skarda, 1981).
3. *Evoked* gamma-activity, which is both elicited by and strictly time-locked to a stimulus. Numerous examples have been studied in different brain regions of human and cat.
4. *Emitted* gamma activity, i.e., activity that is not bound to a stimulus but rather to an internal process, which has been demonstrated, for instance, by use of the ‘omitted stimulus’ paradigm in non-mammalian vertebrates like fish

(Bullock *et al.*, 1990) or mammals like the cat (Başar-Eroğlu and Başar, 1991).

From the late 1990s to the present date, a sixth phase is observed, during which research on gamma activity is strongly started by also discussing the effects of neurotransmitters (Traub *et al.*, 2003; Whittington *et al.*, 2000). Further, several studies suggested that 40-Hz oscillatory activity is not restricted to sensory processing, but can also be modulated or triggered by cognitive processes (Tiitinen *et al.*, 1993; Pulvermüller *et al.*, 1995; Tallon-Baudry *et al.*, 1998). Başar *et al.* (1995) argued that gamma responses occur throughout the brain, i.e., in a selectively distributed way, as correlates of brain functions, which can also be sensory and cognitive in origin.

The seventh phase, which began during the 2000s, is shaped by strategies on cognitive gamma responses and also by an increasing number of studies on cognitive impairment.

Hermann *et al.* (2004) distinguish evoked gamma- and induced gamma oscillations as follows: Oscillations in the brain can either occur *spontaneously*, that is, without relation to external stimuli, or they can be related to the processing of stimuli. In the latter case, a distinction is usually made between ‘*evoked*’ and ‘*induced*’ oscillations (Başar-Eroğlu *et al.*, 1996b). If an oscillation appears with the same latency and phase after each stimulus, it is considered *evoked activity*, which is usually the case for early gamma activity prior to 150 ms following stimulus presentation (peak latencies are typically around 50 ms for auditory, and around 100 ms for visual stimuli) (See also Figure 2).

Hermann *et al.* (2004) also indicated that if the oscillation varies in either latency or phase between trials, it is termed *induced activity*. This is typically the case for late gamma activity, which occurs 200–300 ms or later after stimulus presentation (See also section 1.2 and Figure 1). Gamma activity appears in a wide frequency band between about 30 and 80 Hz. Evoked responses often oscillate around 40 Hz, whereas induced responses might also reveal higher frequencies. Computation of the average potentials across many experimental trials usually employs electrophysiology to yield the event-related potential; evoked oscillations are therefore summed, because they are phase-locked to stimulation. Induced activity, on the



other hand, almost cancels out completely in the averaged event-related potential. It is notable that induced oscillations are highly reduced in the averaged curves, but are never cancelled out if the number of epochs do not attain high trials (See example in Figure 1a).

P300 - 40 Hz RESPONSE IN HIPPOCAMPUS

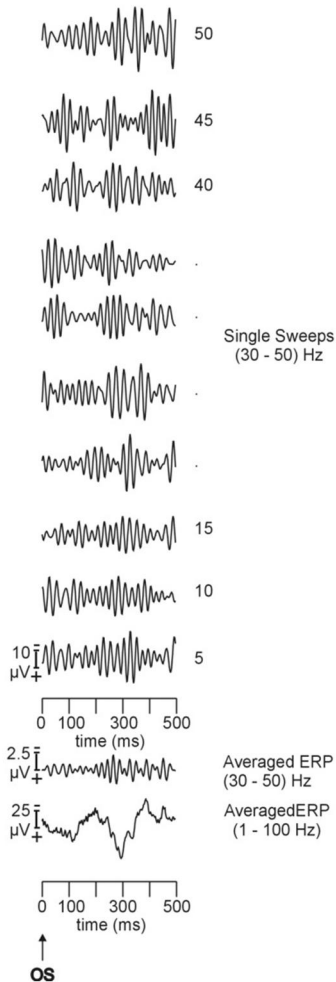


Figure 1a. Event-related potentials of the lower pyramidal layer (CA3) of hippocampus (one cat). Top: Single ERP sweeps (epochs) filtered at 30–50 Hz; Middle: Averaged ERP filtered at 30–50 Hz; Bottom: Unfiltered ERP, average of 50 artifact-free epochs (Modified from Başar-Eroğlu *et al.*, 1991) OS: The time marker of the omitted stimulation. The gamma responses are time-locked to omitted stimulation.

1.2 Superposition of P300 Component with emitted gamma response

Several investigations dealt with *cognitive processes* related to gamma responses, some of which were based on measuring the P300 waves. This positive deflection typically occurs in human ERPs in response to “oddball” stimuli or omitted stimuli, interspersed as “targets” into a series of standard stimuli:

A *P300–40-Hz component* has been recorded in the cat hippocampus, reticular formation, and cortex (with omitted auditory stimuli as targets). This response occurs approximately 300 ms after stimulation, being superimposed with a slow wave of 4 Hz, illustrated in Figure 1a (Başar-Eroğlu and Başar, 1991). The paradigm used was as follows:

The chronically implanted, freely-behaving cats heard tones of 2000 Hz and 80 dB with regular intervals over a long period of time. In the second stage of the experiments, every fifth tone was omitted. In the course of such experiments, induced 40-Hz oscillations were observed in the cat hippocampus. Figure 1b shows approximately 10 single EEG-epochs as responses to omitted stimuli, with a passband of 30–50 Hz.

Preliminary data indicate similar P300–40-Hz responses to oddball stimuli in humans (Başar-Eroğlu *et al.*, 1992; Gurtubay *et al.*, 2001). However, a suppression of 40-Hz activity after target stimuli has also been reported (Fell *et al.*, 1997).

Several investigations dealt with *cognitive processes* related to gamma responses, some of them based on measuring the P300 wave. This positive deflection typically occurs in human ERPs in response to “oddball” stimuli, or to omitted stimuli interspersed as “targets” into a series of standard stimuli:

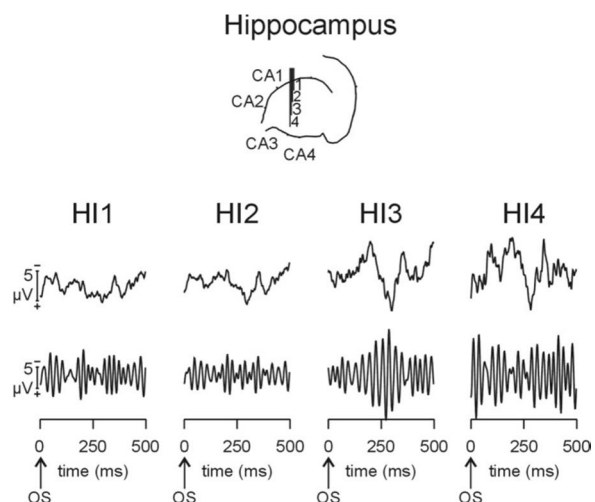


Figure 1b. Grand averages (mean values from 8 cats) of ERPs in various layers of hippocampus. Top: Location of multi-electrode; CA1 and CA3 corresponding to HI1 and HI3/HI4, respectively. Middle: Unfiltered ERPs; Bottom: Filtered ERPs (30–50 Hz; OS: omitted stimulation) (Modified from Başar-Eroğlu *et al.*, 1991).



Figure 1b describes that such 40-Hz response bursts associated with omitted stimuli have maximal responses in the CA3 layer of the hippocampus, and that a slow wave of approximately 4 Hz is superimposed with these gamma responses, occurring 300 ms following the omitted stimuli. This P300–40 Hz response has pure cognitive causality, and possibly corresponds to the induced late gamma response described by Hermann *et al.* (2004). This is an example of analysis including a task associated with event-related oscillations; and also an example of cognitively-induced gamma rhythms superimposed with a low-frequency oscillatory response.

No gamma responses are seen at the time of the omitted stimulus, because there is no physical stimulation. Thus, the response observed at around 250–300 ms is purely cognitive in origin. This experiment clearly demonstrates an intracranial cognitive response occurring around 250–300 ms, most probably following subcortical interplay in the fronto-parietal–hippocampal circuit.

In order to understand the cognitive response observed approximately 300 ms after cognitive stimulation, it is useful to examine the neuro-anatomic and functional organization in the brain.

2. Connections of the Sensory-Cognitive Systems in the Brain

In order to understand the multiple gamma band responses, it is important to describe the connections in sensory cognitive systems of the brain. Certainly, the connections in the brain are very complicated; however, Flohr (1991) described the anatomical connections in the brain in a simplified and transparent manner, illustrated in Figure 2.

1. *In the illustration, specific afferents from sense organs reach specific thalamic nuclei before the primary cortical areas.* For instance, auditory information is transmitted through the medial geniculate nucleus to the primary auditory area; visual afferents are transmitted through the lateral geniculate nucleus to area 17 of the occipital cortex.

2. *Non-specific afferents reach the cortex from the mesencephalic formation.* It has now been established that reticular formation is connected to different nuclei with specific afferent connections. There is a second site where the reticular formation influences the processing of primary afferents: the thalamic relay nuclei. The nucleus reticularis thalami, a thin sheet of neurons, surrounds the dorsal thalamus and inhibits the thalamic relay nuclei. Its control function is, in turn, affected by collaterals of thalamo-cortical pathways, by collaterals from cortico-thalamic projections, and by inhibitory afferents from the mesencephalic reticular formation. There are important connections within the cerebral cortex, involving the association areas. Primary auditory, somatosensory, and visual fields each project to adjacent unimodal association areas, which, in turn, project to secondary unimodal association fields. The unimodal association areas project to a number of polymodal sensory areas, located in the cingulate gyrus, parietal-, temporal-, and frontal lobe. The functions of these areas are vaguely

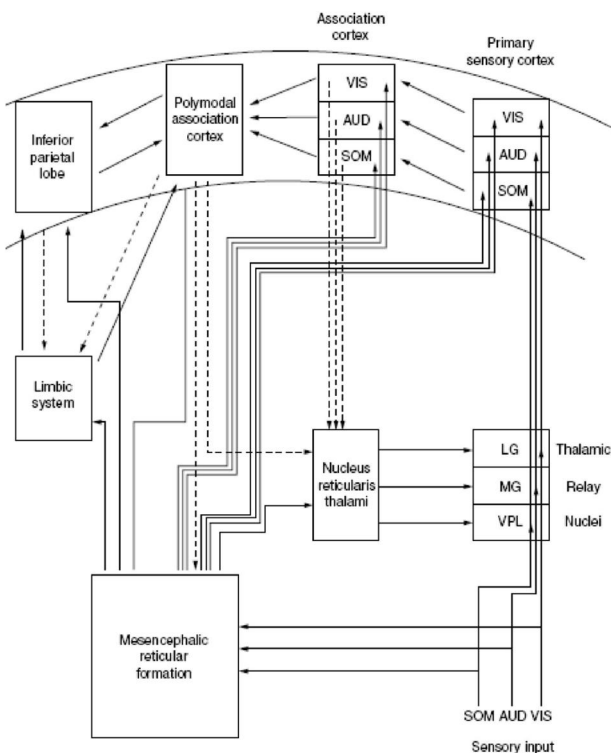


Figure 2. Flow of information in the auditory, somatosensory, and visual pathways, reticular formation, limbic system, and association areas of the cortex (Sensory and cognitive neural pathways in this figure are modified from Flohr, H. [1991] *Theory and Psychology* 1: 245–262).



described as a crossmodal association and synthesis. The polymodal association areas project to the inferior parietal lobe, which has been termed a “supramodal” area. Polymodal and supramodal regions have connections to the limbic system; these connections provide the anatomical substrate by which motivational states influence cortical processing of sensory stimuli.

Every sensation in the brain also induces cognitive loading, at least for matching processes. Furthermore, all the presented cognitive targets evoke sensations; the respective neural processes are interwoven and require, for final processing, at least three neural loops next to purely sensory connections in the simple sensory systems. These loops are: 1. “Secondary connections” to the cortex over reticular formation; 2. “Secondary connections” over the limbic system; 3. “Connections within the cortex” between association areas; 4. In summary, there are 4 loops, one of which provides transfer of almost pure sensory information

Several studies using intracranial recordings from the rat brain (Miller, 1991) and human brain (Dastjerdi *et al.*, 2011) indicated that cortico-cortical interplay occurs after sensory-network and hippocampal-cortical network activation. (Miller, 1991) estimated a hippocampal-cortical loop time in the range of 120–200 ms from rat intracranial recordings. In human intracranial recordings, upon a cognitive task, Dastjerdi *et al.* (2011) demonstrated the cortical activation in lateral parietal cortex, after approximately 300 msec. Therefore, taking these intracranial recording findings into consideration, it is reasonable to assume that the beginning of the cortico-cortical interplay starts around 300 msec poststimulus.

As stated previously, at the time of the omitted stimulus, no gamma responses are seen, because there is no physical stimulation. Thus, the response at around 250–300 is purely cognitive. This experiment clearly demonstrates an intracranial cognitive response, which occurs at around 250–300 ms, most probably following a subcortical interplay in the fronto-parietal-hippocampal circuit.

3. Methods

3.1 Subjects

Five subjects (4 females, 1 males; age 19 to 28 years) volunteered for the experiment. All subjects were university students and university members, all were right-handed, and all had completed at least 10 years of education. The subjects were interviewed with a questionnaire for their family history, demographic characteristics, medical profiles, and drinking habits. None of the subjects reported any current or past neurological or psychiatric illness, and all had normal or corrected-to-normal vision. All subjects signed an approved consent form.

3.2 Stimulation

The participants sat in a dimly lit, isolated room during recordings. Two types of stimuli were presented: simple visual stimuli and visual oddball paradigm. First, simple visual stimuli were presented in the form of a light (10 cd/m² luminance) with inter-stimulus intervals varying between 3 and 7 s. Then, a classical visual oddball paradigm was applied by using the simple 10-cd/m² luminance light as the standard and a 40-cd/m² luminance light as the target stimuli. The light appeared at full size on a 19-inch computer monitor with a refresh rate of 60 Hz. The duration of the stimulation was 1000 ms. The probability of the deviant stimuli was 0.33 and, in all paradigms, they were embedded randomly within a series of standard stimuli. These stimulation signals were applied randomly, with inter-stimulus intervals again varying between 3 and 7 s. In order to assess focused attention and working memory, the task required mental counting of the target stimuli.

3.3 Electrophysiological recording

EEG was recorded with 30 Ag/AgCl electrodes mounted in an elastic cap (Easy-cap) according to the international 10–20 system. Additionally, two linked earlobe electrodes (A1 + A2) served as references. The EOG from the medial upper- and lateral orbital rim of the right eye was also registered. For the reference electrodes and EOG recordings, Ag/AgCl electrodes were used. All electrode impedances were less than 10 k Ω . The EEG was amplified by means of a Brain Amp 32-channels DC system machine with band limits of 0.01–250 Hz. The EEG was digitized on-line with a sampling rate of 500 Hz.



Artifacts were eliminated by manual off-line selective averaging, taking into consideration the EOG recorded from the right eye. The sweep numbers were equalized randomly between the target and simple visual stimulation conditions.

3.4 Data Analysis

Inter-trial coherence (ITC) is a frequency-domain measure for the synchronization of activity at a particular latency and frequency for a set of experimental events to which EEG data trials are time-locked (Delorme and Makeig, 2004). Here, we calculated the ITPC using EEGLAB (see Delorme and Makeig, 2004) as follows:

For $j = 1$ to N trials,

$$\begin{aligned} \text{ITPC}(t, f) &= \frac{1}{N} \times \left| \frac{\sum_j W_j(t, f)}{|\sum_j W_j(t, f)|} \right| \\ &= \frac{1}{N} \times \left| \sum_j \exp(i\phi_j(t, f)) \right| \end{aligned}$$

where $\phi_j(t, f)$ is the phase of the wavelet at time t and frequency f . ITPC values range from 0 (indicating absence of phase-locking) and 1 (indicating perfect phase synchronization). All ITPC values were baseline-corrected over -300 ms to -50 ms and were computed for each participant for grand average, ITPC values were averaged across all participants.

At this stage, the application of statistical analysis would be misleading. There are several parameters and frequency windows to consider, and therefore reliable statistical interpretation would be possible only after the analysis of a larger dataset. Presently, we evaluated data from only five subjects, which should be regarded as pilot data.

4. Fine Structure of Late Gamma Responses of the Brain

According to Figure 2, sensory stimulation would reach the sensory cortices with short latency, eliciting a faster response than those elicited by stimuli containing a cognitive task. The signal with cognitive tasks would reach the cortices over reticular formation and/or the limbic system. Additionally, there are connections in the cortex with reverberations between association areas (Figure 2, arrows in

both directions: up and down). Accordingly, it is to be expected that phase-locked or time-locked responses following cognitive inputs—for example, target stimulation of the P300 oddball paradigm—would elicit late responses in comparison to simple stimuli.

The experimental results confirmed this theoretical assumption:

We analyzed evoked and event-related light-responses from 10 subjects by means of adaptive digital filtering (based on evoked and event-related spectral analysis). Further, we analyzed the results from the 10 subjects by means of a phase-locking method (ITC).

In our earlier studies, we emphasized the importance of evoked and event-related power spectral analyses prior to any type of dynamic systems analysis in order to first obtain a global indication of the spectral composition of brain response.

In this report, we do not aim to give a detailed description of power spectra or the time course of adaptively filtered responses. The power spectra do not give an exact account related to phase- or time-locking. We only indicate that, globally, there are several peaks in evoked and event-related power spectra within the gamma frequency band; and that there are more abundant peaks in higher frequencies around 40–45 Hz in event-related spectra compared to evoked spectra. Further, in event-related spectra the relevant maximal peaks are shifted to higher frequencies of greater than 35 Hz and mostly around 40 Hz. This was expected, following the anatomic–functional descriptions stated in section 2.

We focus, in this report, on plots of inter-trial coherences. Since the grand averages of 5 subjects are in good accordance with plots of single subjects, we perform here only an analysis with grand averages.

4.1 Phase Locking in Visual Evoked Oscillations

Occipital cortex:

In the occipital cortex, during the first 100–200 ms, solid inter-trial phase locking (approximately 0.40) is observed in the range of the 28-Hz frequency window (Figure 3a). In contrast, the phase locking in frequencies higher than 28 Hz is weakened (approximately 0.25). No phase locking is observed in the late



time window (later than 30 ms). Further it is to indicate that ITC depicts two maximal peaks, at 100 and 200 ms (corresponding to a 10-Hz periodicity). These results confirm the time-locked 10-Hz response in visual occipital responses encountered in the neuroscience literature, as reviewed by Başar (2012) and Başar and Güntekin (2012). At around 400–600 ms post-stimulus a weak time-locking of approximately 0.02 is observed. However, this is a very weak effect compared with the results

for event-related ITC, illustrated in Figures 3a and 3b.

The ITC analysis of frontal F₄ response (N=5) showed similar results, with the solid phase-locking of 0.40 being focused in the 200 ms time window. However, the double maxima in the 200 ms range, which was observed at location O₂, was reduced to only a single peak at the lower frequency band of 28 Hz (Figure 3b), possibly indicating the reduction or weakening of the 10-Hz periodicity.

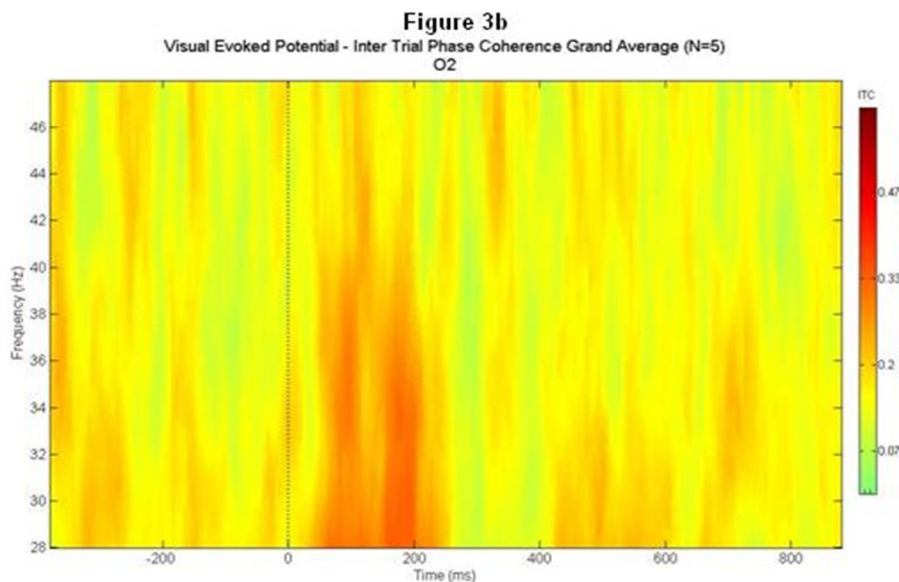
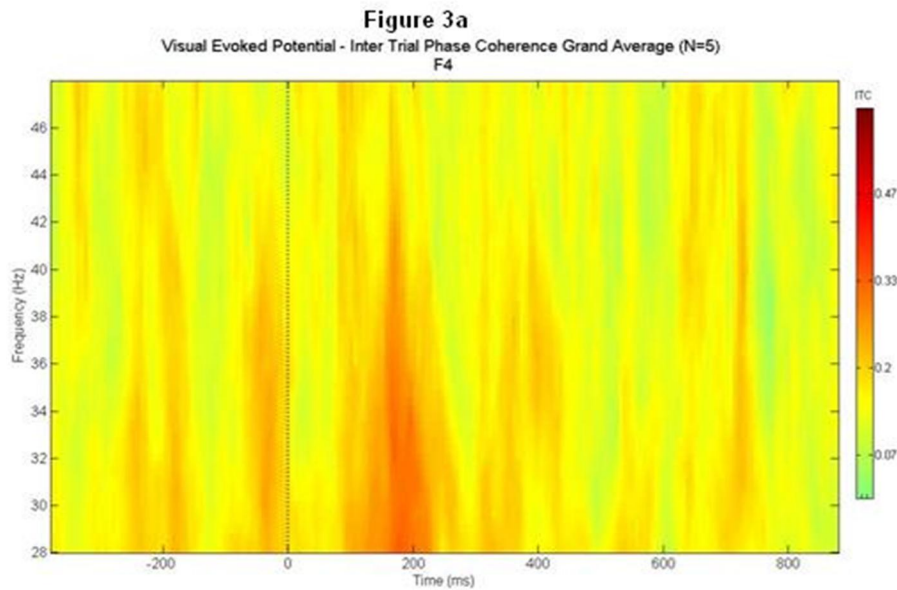


Figure 3. The grand average plots of inter trial phase coherence as grand average of 5 subjects.



4.2 Phase Locking in Event-related Oscillations (Target Response in Oddball Paradigm)

In ITC plots of EROs (Figures 4a and 4b), the general time course and frequency composition is completely changed.

- 1) At O₂ location, there are phase-locked components at 400 and 600 ms, in addition to phase locking at around 100 ms; b) Moreover, the frequency of phase-locked oscillations was shifted to higher frequencies than 40 Hz (200 ms)

periodicity, indicating a superposition with the 5-Hz frequency band. There are abundant phase-locked response components in comparison to sensory-evoked responses in Figure 5.

- 2) At F4 location, the picture is similar to O₂ responses. There is a 10-Hz periodicity at 100–200 ms, with lower frequencies around 30 Hz, whereas at around 600 ms, a solid phase-locking (0.45) with frequency greater than 40 Hz is recorded.

Figure 4a

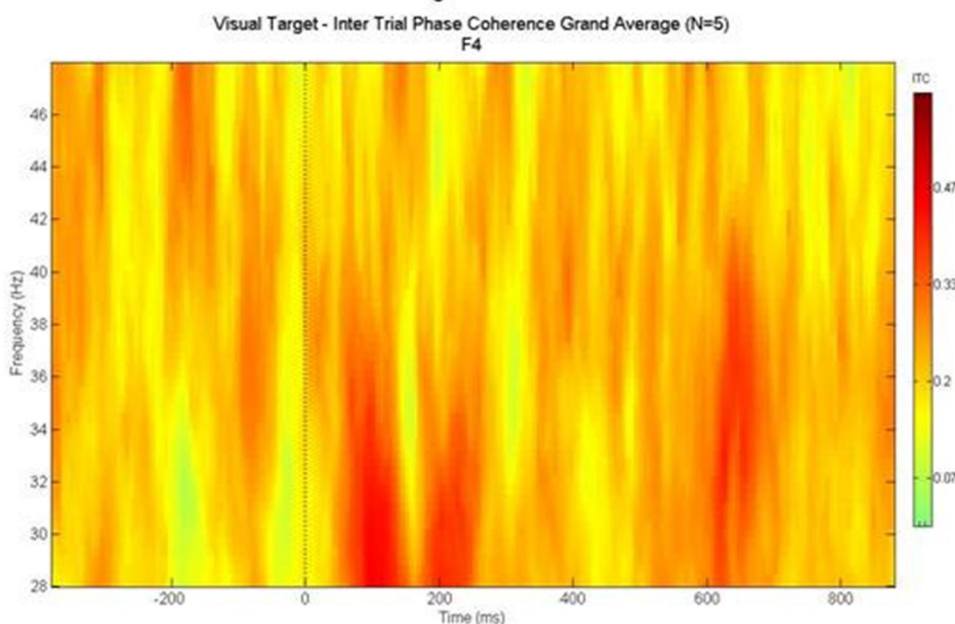


Figure 4b

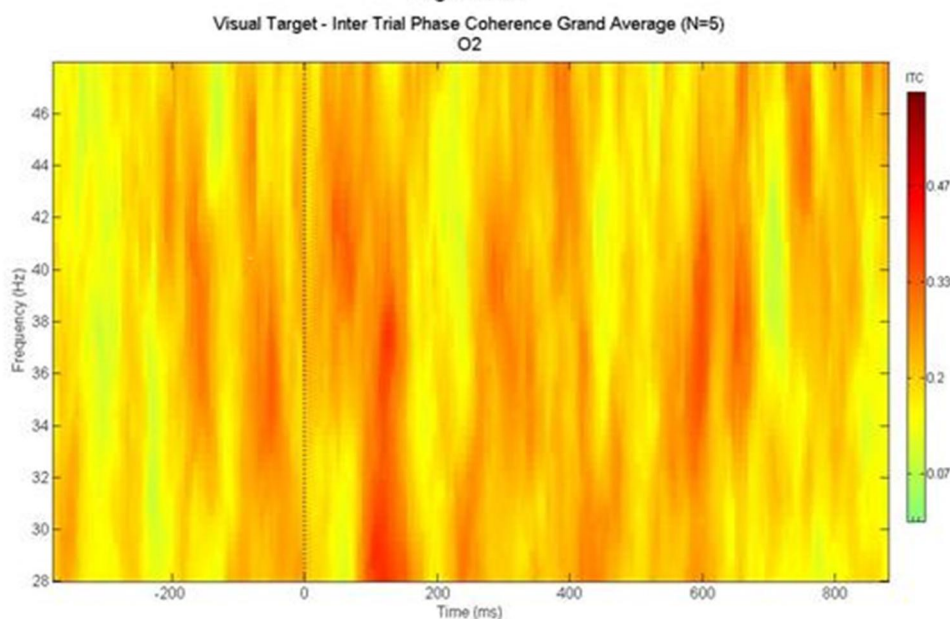


Figure 4a and 4b. The grand average plots of inter trial phase coherence as grand average of 5 subjects.



5. The Link between Two States of Uncertainty: Chaotic Behavior or Quantum-Like Behavior

5.1 Two Types of Uncertainties: Web of Chaotic Brain/Quantum Brain

In his book on chaos, Gleick (1987) advocates that new science goes so far as to say that “twentieth-century science will be remembered for just three things: relativity, *quantum mechanisms*, and *chaos*.” In other words, chaos has become the century’s third great revolution in the physical sciences. Like the first two revolutions, chaos cuts away at the tenets of Newtonian physics. Could this development also be useful and of great importance in brain research? The brain is a *nonlinear system* par excellence. Accordingly, in the last three decades, the concepts of chaotic dynamics have found an important application within research on compound electrical activity of the brain.

Why does the brain behave as a chaotic system? This can be explained on three fundamental levels. In several structures of the brain, there are various groups of neural oscillators in at least seven frequency channels. Therefore, the brain has a large number of degrees of freedom related to those activities. Accordingly, the dimension of possible states of substructures within the brain, or of the whole brain, is high. In a chaotic system, small changes in initial conditions may give rise to large changes in the trajectory of the system.

On the contrary, the quantum-like “uncertain” behavior of a brain structure can be observed even by few neurons behaving similarly. However, the dimension of the studied brain structure, which consists of only a few neurons, does not show chaotic behavior. Nevertheless, upon excitation, such a structure can also behave in a probabilistic manner or behave in an in-deterministic way: The neuron (neurons) may fire or not fire. Once a neuron is firing, the experimenter is no longer able to excite the neuron as at the beginning. A good example can be given by describing a session using light stimuli on a human subject. Only a unique stimulation may cause increased alpha activity, and the second stimulation will not find the neuron or neuron groups at the same functional level.

In 1983, Başar proposed to model the brain using the S-matrix in quantum mechanics, where cross-sections of production

of elementary particles are predicted, as a metaphor. In neural mechanisms, quantum processes are not as yet observed; this represents a parallel to uncertainty dynamics. This proposal was further developed within a framework of super-synergy in the brain (Başar, 2006). The laws of quantum physics have statistical characteristics. This means that they are valid not for a single system but for an aggregation of identical systems; accordingly, they cannot be confirmed by measurements on one individual, but only by a series of repeated measurements from that individual. As in quantum physics, laws on the brain in specifically cognitive processing are valid for a great on aggregations of individual units. They are valid not for single neurons but for neural populations. What applies to quantum mechanics also applies to the dynamics of chaotic systems. In systems, not properties but probabilities are described; laws disclose the changes in probabilities over time; and they are valid for congregations of units. It appears that, for the comprehension of event-related potentials (ERPs), a new set of parameters on the paramount EEG must be considered, which is tentatively named “brain indicators”.

In Einstein’s words, “*Quantum physics formulates laws that govern crowds and not individuals; not properties but probabilities are described*” (Einstein and Infeld, 1938). Laws do not disclose the future of systems, but govern the temporal changes in these probabilities. Similar to quantum physics, in cognitive processing, the laws of the brain are valid for large populations of individual units. Rules for excitation are not valid only for single neurons, but also for neural populations. What applies to quantum mechanics also applies to the dynamics of chaotic systems. In both systems, *not properties, but probabilities* are described; laws disclose the change of the probabilities over time; and they are valid for congregations of units.

A given substructure of the brain or a brain tissue, in fact, shows that both properties can be observed together. Single neurons may behave with uncertainties originating from the nature of neurons, similar to quantum systems; and “*chaotic uncertainty*” resulting from the existence of high dimensionality. This can be interpreted as a result of the existence



of several oscillatory frequencies that give rise to higher degrees of freedom.

It is straightforward to explain why the brain behaves as a chaotic system. In various structures of the brain, there are several groups of neural oscillators in at least seven frequency channels. The brain therefore has a large number of degrees of freedom related to those activities. Accordingly, the dimension of substructures of the brain or the whole brain is high. Previous sections discussed that chaotic behavior and uncertainty is caused by this high-dimensional system. In a chaotic system, small changes in initial conditions may give rise to large changes in the trajectory of the system. On the contrary, the quantum-like behavior of a brain structure can be observed even by few neurons behaving similarly. Accordingly, the dimension of the studied brain structure consisting only few neurons does not show chaotic behavior. However, upon excitation, such a structure can also behave in a probabilistic manner or behave non-deterministically: The neuron (neurons) may fire or not fire. Once a neuron is firing, the experimenter is anymore unable to excite the neuron as at the beginning.

6. Discrete Eigenvalues of Phase Locking in the Gamma Frequency Band

6.1 Discrete Eigenvalues

Generally, quantum mechanics does not assign definite values. Instead, it makes a prediction using a probability distribution. This means that it describes the probability of obtaining the possible outcomes from measuring an observable event. Often, these results are skewed by many causes, such as dense probability clouds. Probability clouds are approximate. The electron location is given by a probability function, the wave function eigenvalue. Naturally, these probabilities will depend on the quantum state at the “instant” of the measurement. Hence, uncertainty is involved in the value. There are, however, certain states that are associated with a definite value of a particular observable. These are known as eigenstates of the observable (“eigen” can be translated from German as meaning “inherent”).

6.2 Brain's probabilistic and strange resonances

As described in section 2, upon visual/cognitive stimulation, the neural signals elicited in the retina are conveyed or transferred from the retina to association areas of the cortex, and finally to the frontal cortex and parietal cortex by means of three neuronal pathways.

Different structures are excited along this complex pathway, the transmission being impossible to describe exactly. However, despite this great complexity, Figures 3 and 4 show that there are preferred time windows depicting phase locking of gamma responses. Frozen temporal structures are not rigid, showing a probabilistic distribution and a gitter pattern.

In Summary

- 1) There are approximately 3–4 gamma responses in 28–30 Hz, 35 Hz, and 40–45 Hz frequency windows.
- 2) Comparison of Figures 3 and 4 shows that cognitive stimulation elicits late responses, usually with higher frequencies. These late responses cannot be considered as after-discharges or prolongation of the early responses. The 300 ms, 600 ms, and 800 ms responses have higher frequency behavior, possibly indicating different sources along the complex pathway.

There are at least 3 transfer lines from sensory receptors to the frontal cortex:

- 1) Direct transmission over thalamus; b) longer connections over reticular formation; b) connection over limbic system .There are also reverse transmission of signals, and possible reverberations.
- 3) Accordingly, the cognitive responses need longer time courses or latencies a higher number of discrete phases locking (The amount of time locked responses are increased in comparison to sensory evoked oscillations).

Figure 5 shows event-related oscillatory response (oddball target) in parietal location of a single subject, which was digitally filtered in the 40–45 Hz frequency window. Here, only a late phase-locked response, starting around 400 ms, is seen. The early response at around 100 ms is not evident. This finding is similar to the late response of the cat hippocampus, shown in Figure 1. This analysis demonstrates the possibility of dissecting event-related responses into different frequency windows



during the time course. The event-related oscillation in the wide gamma band is a compound oscillation containing several superimposed sub-gamma oscillations with heterogeneous frequencies.

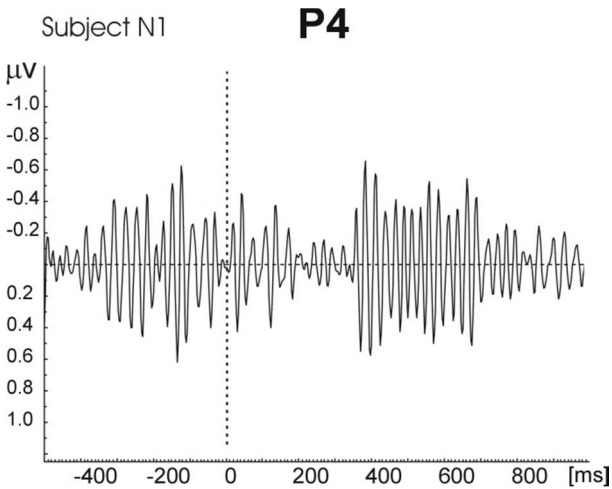


Figure 5. Late parietal response of a single subject in the 40–45-Hz frequency window. The early response in the first 100 ms is missing.

7. Conclusion

- Phase-locking analysis confirms our earlier results related to gamma cognitive responses 300 ms after omitted stimuli in cat hippocampus and human scalp recordings (see Figure 1). Cognitive responses are late; moreover, they have higher frequencies.
- There are at least 3–4 phase/time-locked gamma responses within the 28–45-Hz frequency window.
- Late responses starting around 300 ms are probably responses that are conveyed over reticular formation, hippocampus, etc., whereas the early response in the primary occipital cortex O1 starting at 100 ms is most probably the direct response over the short pathway over lateral geniculate nucleus.
- Eigenvalues or nodes: It is remarkable that nodes or Eigenvalues are observed, despite the complexity of the pathways and the superposition of several oscillations.

- It appears that the event-related oscillations in the gamma band undergo an increasing frequency modulation. The time course in the first 200 ms has lower frequencies of approximately 28–30 Hz. With increasing time, the frequencies of these oscillations reach values of up to 46 Hz.
- However, this frequency modulation does not occur in an analog way, as there are almost discrete frequency jumps with periodicities of around 10 Hz (at the beginning), and 5 Hz with progressing time at longer than 300 ms following stimulation. Interplay or incorporation with alpha response and theta response are possible (see the periodicities in Figures 3 and 4)
- The discrete oscillatory packages are separable or can be dissected by application of different stimulation modalities. These separations can also be observed as topographic changes. For example, simple visual stimulation at the occipital cortex triggers 30-Hz oscillatory response at the first 200 ms upon stimulation. Other secondary or tertiary oscillatory responses were not recorded at the occipital cortex upon simple visual stimulation (Figure 3). On the contrary, cognitive inputs (target stimulation) elicit secondary at tertiary responses at around 400 ms, 600 ms, and sometimes also at around 800 ms. These late oscillatory responses are probably due to longer signal transmission over the pathways described in Figure 2. It will be not simple to exactly describe the correlations between responses in cortical areas and time courses of phase-locking processes.
- 8) This type of analysis is likely to become very important for the understanding of electrophysiology in cognitive impairment.

However, the time/phase-locking of responses occur in discrete time intervals and have probabilistic distribution.



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