Time and Frequency Analysis of the Brain's Distributed Gamma-Band System

During the past 15 years, our research group has published several reports about a working hypothesis on the brain's electroencephalogram (EEG) and evoked potentials (EPs). This hypothesis has several interrelated issues. In our view, the conventional averaged EP—which is widely used and very popular—was considered only as a rough estimate of the brain's EEG-response, and it was claimed that the averaged EP does not take into account dynamical changes in the brain's intrinsic activity. On the contrary, both single EPs and EP-like EEG segments probably resulting from hidden sensory or cognitive stimulation were considered as the brain's quasi-invariant resonant modes containing important brain frequency codes related to central nervous system function [1-4]. The hypothesis explained in the literature can be summarized as follows:

1) The EEG consists of the activity of an ensemble of generators producing rhythmic activity in several frequency ranges. Usually, these oscillators are active in a random manner; however, by application of sensory stimulation, these generators are coupled and act together in a coherent way. This synchronization and enhancement of EEG activity gives rise to an "evoked" or "induced rhythmicity" ("alpha response," "theta response," "40 Hz (gamma) response" etc.). Evoked potentials representing ensembles of neural population responses were considered as a result of transition from a disordered to an ordered state (For details of this analogy also in the view of synergetics see [1, 2, 5]).

2) These rhythmicities may also occur without defined physical stimulation, but may be triggered by hidden sources, for example as a result of cognitive loading (internally induced rhythmicities) [6].

3) The superposition of induced or evoked oscillations in various EEG-frequency channels (4 Hz, 10 Hz, 20 Hz, 40 Hz etc.) gives rise to the compound EP. These frequency channels are related to the main peaks in the amplitude frequency characteristics (AFC) computed from the compound EP (for the method of computing AFCs, see below). To analyze EPs, we have used response-adaptive digital filters with cut-off frequencies chosen according to the main AFC peaks. By using such filters, we can visualize an enhancement following the stimulation, and a damped sinusoidal waveform, which we have called "evoked theta/evoked alpha" or "evoked 40 Hz," depending on the frequency of these damped oscillations.

The description of resonance phenomena in neural tissues in various frequency ranges has gained emphasis. New reports concerning the cellular level [7-12] agree in proposing the important role of resonance phenomena in brain signaling.

Time and Frequency Analysis of EPs

The analysis of resonance phenomena of the brain requires a set of methods that permit time and frequency analysis of the EEG and evoked potentials.

Resonance Phenomena

Resonance is the response that may be expected of underdamped systems when a periodic signal of a characteristic frequency is applied to the system. The response is characterized by a "surprisingly" large output amplitude for relatively small input amplitudes, i.e., the gain is large.

Resonance phenomena or responses to forced oscillations can be analyzed in a direct empirical way as follows: A sinusoidal signal of a frequency $f$ is applied to the system. After a certain period, sufficient for the damping of the transient, only forced oscillations will remain, having the frequency of the applied signal. Then the amplitude of the applied signal (input), the amplitude of the forced oscillations (output), and the phase difference between input and output are measured. Gradually increasing the frequency from $f=0$ Hz to $f_f$, the output amplitude relative to the input amplitude and the phase differences will be measured as a function of frequency (amplitude characteristics and phase characteristics [13]).

Although this approach reveals the natural frequencies of a system, only a small number of workers have investigated the behavior of the EEG response using sinusoidally modulated light and sound signals (for details on pioneering experiments, see [14]). Difficulties result from the requirement for evoked responses to sinusoidal signals of over at least three decades of stimulation frequencies, evoked responses in each stimulation frequency being averaged using at least 200 stimuli. Another difficulty comes from the frequent changes in brain activity stages. They may change within a few minutes and have a limited duration, which is not sufficient for the application of sinusoidal stimuli of different frequencies.

Analysis of Resonance Phenomena

There is, however, another way of obtaining the frequency characteristics of a system: the transient response frequency characteristics method. According to general systems theory, all information concerning the frequency characteristics of a linear system is contained in the transient response of the system, and vice versa. In other words, knowledge of the transient response of the system allows one to predict how this system would react to different stimulation frequencies. If the step response, $c(t)$, of the system (in our case, the sensory evoked potential) is known, the frequency characteristics, $C(j\omega)$ of this system can be obtained with a Laplace
transform, i.e., a one-sided Fourier transform:

\[ G(j\omega) = \frac{1}{2\pi} \int_{-\infty}^{\infty} d(t) \exp(-j\omega t) \, dt \]

(\(\omega = 2\pi f\), where \(f\) is the frequency of the input signal).

The frequency characteristics \(G(j\omega)\) including the information of amplitude changes of forced oscillations, and the phase angle \(\varphi\) is also called the frequency response function, \(k\) is a special case of the transfer function and is, in practice, identical with the transfer function.

The amplitude frequency characteristics \(|G(j\omega)|\) and the phase angle \(\varphi\) can be obtained by numerical evaluation — using a Fast Fourier transform — with the help of a digital computer.

Although this transform is valid only for linear systems, it can be applied to nonlinear systems as a first approach [1]. The errors due to system nonlinearities are smaller than errors resulting from the length of measurements in sinusoidal stimulation experiments, given the rapid transitions of the brain's activity from one stage to another.

Finally, a limitation of this approach has to be mentioned: by application of sensory stimuli, the brain is not directly excited with the proper input signal. There are physiological transducers (cochlea, retina, skin) between the input signal and the measured electrical output. Therefore, a direct comparison of the input and output signals is impossible. Instead, the relative output amplitudes — or the magnitude of the maxima in the amplitude characteristics — are to be compared.

A Frequency Method in the Time Domain

Digital filtering of EPs is based on the following principles (for details, see [15]): Band pass filters allow, in a desired frequency band, the maximum transmission from input to output. In other frequency bands, the output is negligible compared to the input. In an ideal filter, in other frequency bands, the transmission is zero. The filters used in our investigations do not introduce any phase shift [15].

The cut-off frequencies of the band pass filters used are chosen only for selected channels or tuning frequencies indicated by clear peaks in the amplitude frequency characteristics. As demonstrated in previous studies, the information obtained with band pass filtering is in good agreement with the information obtained by AFCs [16, 17].

Furthermore, digital filtering provides information not visible in the amplitude frequency characteristics: it is possible to visualize the time course of an oscillatory signal component. In this way, the time coupling between an external or internal event and the response components in various frequency bands can be investigated.

"Response adaptive filtering" requires that filter limits be chosen according to the frequencies and bandwidths of maxima in the AFCs. The cut-off frequencies used in our study, however, are in agreement with previous studies and have proven to be suitable for the analysis of global resonance phenomena of brain structures: 0.5-3.5 Hz ("delta"), 4-7 Hz ("theta"), 8-15 Hz ("alpha") and 15-30 Hz ("beta"); for higher frequencies — e.g., gamma (30-70 Hz or "around 40 Hz") (see below and [18, 19]).

Figure 1 shows the relation of amplitude frequency characteristics and curves obtained by digital filtering.

Practical Steps in EP Time and Frequency Analysis

The experiments summarized in this article included both scalp recordings from human subjects and intracranial recordings from chronically implanted electrodes in freely moving cats. The methodology to evaluate EPs, AFCs and digitally filtered data was described previously [1]. The essential steps are as follows:

1. Recording of EEG-EP epochs: With every stimulus presented, a segment of EEG activity preceding and the EP following the stimulus were digitized and stored on computer disc memory. This operation was repeated about 100 times.

2. Selective averaging of EPs: The stored raw single EEG-EP epochs were selected with specified criteria after the recording session: EEG segments showing movement artifacts, sleep spindles or slow waves were eliminated.

3. Amplitude frequency characteristics were computed according to the formula given above.

4. Digital filtering: EP frequency components are computed using digital filters without phase shift [15]. The cut-off frequencies of the band pass filters used are not arbitrarily chosen. Filters are applied only for selectivity channels, or tuning frequencies indicated by clear peakings in the amplitude frequency characteristics.

The essential mathematical procedures applied are schematically illustrated in Fig. 2.

Possible Physiological Roles of Frequency Components

After introducing our methods, we will present examples of induced rhythmicities to be observed in EPs, event-related potentials, and related fields. These examples will be classified by the events giving rise to the respective potentials: rhythmicities due to external events will be dealt...
The rhythms spontaneously existing in EEG include delta (0.5-3.5 Hz), theta (4-7 Hz), alpha (8-15 Hz), and beta (15-30 Hz) frequency ranges. The rhythms in the 4-10 Hz band (theta rhythms) and around 10 Hz (designated the alpha band) are mentioned. Some authors have reported evoked, induced or emitted rhythms in the EEGs (e.g., ERPs), which are correlated with external and/or internal events [1, 2, 8, 9, 11, 20-28].

What are the functional roles of induced rhythms? On the basis of experimental data (see, e.g., the contributions to the volume "Induced Rhythms in the Brain" [26]), three topics concerning integrative aspects of brain signaling have been suggested as points of entry into the problems of induced rhythms:

1. Can a single principle underlying high order neural processing be isolated? Or are there instead of a fundamental common principle—multiple principles, some of them observable and some others beyond our scope?
2. Are there general transfer functions in neural tissues of the brain? That is, can the transfer functions we compute have a common basis or meaning?
3. A general principle of high order neural processing may include analogies to the emergence of regular patterns from uniform matter: what is the role of dynamic pattern building? Concerning this topic, both tools of chaotic dynamics and concepts of Kitzchalsky's [29] NRP workshop (1974) have gained importance during the past few years [26].

Keeping in mind the idea that induced rhythmicities may be part of a general principle, we can distinguish four categories of rhythmicities—embracing both induced and spontaneous: (1) Rhythms around 10 Hz (designated the alpha band); (2) those around 40 Hz (gamma band); (3) those in the 4-10 Hz band (theta rhythms); (4) those around the 2 Hz (delta waves).

Spatio-temporal aspects of EEG activity, expressed in terms of synchrony and coherence, may be important in integrating oscillatory neural activity. The synchrony of alpha activity may be one sign of cooperative phenomena whose mechanisms are still to be uncovered [6]. Another example is the micro-EEG revealing spatio-temporal aspects of EEG synchrony [30].

Oscillation and resonance in neural tissues are variables with a certain degree of independence from each other and from the foregoing synchrony and coherence. At the cellular level, thalamic neurons have been found to behave as oscillators and resonators [7]. Oscillation and resonance are possible conceptual approaches to link spontaneous and induced rhythmicities [8-11, 23, 24]. An analysis of resonance phenomena in the EEG—the relationship between spontaneous and induced rhythms—contributes to the understanding of the differences between adults' and children's evoked potentials [31, 32].

Is external stimulation a prerequisite for exciting the brain? Internal events exciting neural tissues can be discovered using special paradigms [6]. Even without such paradigms, it is possible to demonstrate that the EEG is not merely "noise," but a "hot signal" related to tasks: this relationship is achieved by methods of chaotic dynamics (see e.g., [28, 33]; [26] gives a collection of papers).

Induced rhythmicities and resonance phenomena may thus be fingerprints of general transfer functions within the brain, demonstrable in field potentials, EEG and magnetoencephalography. Experiments show brain responsiveness (resonances) to various stimuli in one of the known EEG frequency channels, i.e., in frequency channels in which the brain is able to show spontaneous rhythmic activity. Gamma band (30-70 Hz) responses recorded from the cat brain in the first 100 ms after stimulation will be presented and discussed in an "exemplary case study" below. Further examples are to be mentioned briefly: The hippocampus of the cat brain gave rise to emitted 40 Hz activity with a latency of around 300 ms following omitted stimuli [19]. In human experiments, a sound or light cognitive target induced alpha rhythmicities prior to target [6]. The occipital cortex responds to light stimulation with 12 Hz oscillatory waveforms, whereas the auditory cortex does not [5, 34, 35]. At the hearing threshold, human subjects do elicit very slow rhythmicities around 2 Hz. We interpreted the 2 Hz induced rhythmicities tentatively as induced rhythms during signal detection or decision making [5].
Case Study — Gamma Band Responses in the Cat Brain

In the class of brain electromagnetic rhythmicities, a rhythm around 40 Hz, which is called 40 Hz (or gamma) rhythm [1, 8-11, 22-26, 36], gained importance in recent years. We will use the term "gamma rhythm" or "gamma band activity," because according to the studies performed up to now, activities with similar characteristics can be shown in the range between 25 to 110 Hz and not strictly tuned at 40 Hz [11, 37].

Overview

The first example of the gamma band activity was described by Adrian [21, 38] in the olfactory bulb of anesthetized cats and rabbits. Later, these phenomena have been extensively studied on the olfactory bulb of the rabbit [22], in different brain structures of the cat [1, 2, 26, 39]; in visual cortex of the cat [8, 9, 11, 23, 24]; in fish brain [28]; and in human scalp and MEG recordings 25, 26, 37, 40-45. Strong behavioral correlates of this rhythm have been proposed [22, 41, 42]. Meanwhile, some studies on the cellular level have shown that 40 Hz bioelectrical oscillations can also exist at the single neuron level as an intrinsic property of the neuron membrane [7] or in local neural networks depending on the time constant of the network for optimal synaptic efficiency [42].

On the other hand, the studies in different species, with different techniques, at various levels of neural organisation, have lead to different interpretations of this EEG rhythm. Some authors [8, 9, 11, 23, 24] proposed that this rhythm should be of cortical origin, whereas Llinás and Ribery [45] defined it as a "brain scan" reinforced by activities in the corticothalamic pathways. Basar et al. [1, 2, 46, 47] proposed that the gamma rhythm is a universal, distributed brain rhythm, which can be recorded in various cortical and subcortical brain structures. An important question arising in review of the gamma band activities, studied in various species with different stimulation and recording techniques, is if all the described phenomena in this frequency range are analogous to each other, or if there are different kinds of gamma rhythms, which can not be discussed in the same category.

Recently, Galambos [37] classified the gamma rhythms recorded in different species into four categories: spontaneous, induced, evoked, and emitted. The spontaneous gamma rhythm contributes at any given moment a fraction of the total EEG energy a brain is generating. The induced gamma rhythm is a series of oscillations following sensory stimulation, which are not time-locked to the stimulus. This type of gamma oscillations is recorded in the olfactory bulb of rabbit and the visual cortex of the cat during stimulation with moving stripes [8, 11, 48]. Evoked gamma is tightly time-locked to an external stimulus, and is this type of gamma band activities which is recorded from human scalp during stimulation with click or flash stimuli [1, 18, 25, 44, 49, 50], and the emitted gamma rhythm is oscillations that follow the omitted stimuli in a train of regular stimuli in fish and cat [19, 27]. According to Galambos' classification, the gamma band responses as studied in the olfactory bulb of the rabbit by Freeman, et al. [22] or in the visual cortex of the cat after stimulation with moving stripes by Gray and Singer [8] and Eckhorn et al. [11] are different from human gamma band responses recorded from the scalp after stimulation with auditory clicks or flash light [37, 40, 43, 44]; Human gamma response is time-locked to the stimulus and with a shorter latency (approximately 25 ms), whereas the cat gamma response is not tightly time-locked to the stimulus and occurs after a longer latency period (minimum 100 ms). As long as measurements carried out in different species are not analogous, any functional interpretation of the gamma band activities and definition of its sources will be incomplete.

This case study deals with gamma band responses in cortical and subcortical structures of the cat, which might be analogous of scalp recorded time-locked human gamma responses. For this purpose, a similar stimulation and measurement technique, as in human experiments, will be used. We will use tone bursts as stimuli and record the field potentials in different structures of the cat brain. Earlier experiments of Basar et al. [1, 2, 39, 46, 47, 51] tried to show that gamma responses time-locked to the stimulation are distributed throughout the cat brain, including the sensory cortex, cerebellum, reticular formation, and hippocampus. Our new study is based on the reanalysis of this phenomenon with a greater number of single sweeps and with new analysis facilities.

Methods for Case Study

The experiments were carried out on seven freely moving female cats with chronically implanted electrodes in the auditory cortex (gyrus ectosylvianus anterior, GEA), dorsal hippocampus (HI), mesencephalic reticular formation (RF), and the acoustical vermis of the cerebellum (CE). For exact electrode positions and further details on the experimental procedures see [19]. The cats sat in a cage in a soundproof, echo-free room which was dimly illuminated. Long and tiring experimental sessions were avoided to eliminate the effects of adaptation.

After recording of the spontaneous EEG of the cats for a few minutes, a standard auditory evoked potential recording was carried out. In each recording session, 2 kHz, 80 dB SPL tones of 1 s duration with 0.5 ms rise-time were applied 100 times, with interstimulus intervals pseudo-randomly varying between 2.5 and 3.5 s (mean = 3 s). One second pre- and post-stimulus EEGs were digitized with a sampling rate of 500 Hz and stored on the hard-disc of the computer.

The methodology for the analysis of auditory evoked potentials (AEPs), amplitude frequency characteristics (AFCs), and digitally filtered data and its theoretical background was described above. The maximal peak-to-peak amplitudes of the filtered responses in predefined time windows were measured. For finding the amplitude enhancement in filtered responses due to stimulation, two time windows were used; in the prestimulus period, from -1000 to 0 ms, and in the poststimulus period from 0 and 200 ms, where the amplitude enhancement and phase-locking of the gamma response could be observed. In this way, any transient gamma wavelet in the 1 s prestimulus period of the averaged EEG-EP occurring due to a phase-locking by chance has been taken into consideration to increase the confidence interval of the statistics. The enhancements in
3. The power spectra computed from the grand average of the prestimulus EEG periods (left column) and the Amplitude Frequency Characteristics of the grand average auditory EPs (right column) of Gyrus Ectosylvianus Anterior (GEA), formatio reticularis mesencephali (RF), hippocampus (HI) and cerebellum (CE) of 7 cats. The peaks in the gamma frequency range (30 - 70 Hz) are indicated by short broken lines.

Gamma band amplitudes in different brain structures due to stimulation have been tested with a two-way ANOVA (stimulation x lead).

Results

The gamma band limits have been selected after the inspection of the AFCs of each animal in each location (not shown). The center frequencies of the gamma peaks varied between 30 and 70 Hz in different cats and in different locations. Therefore, broad gamma band filtering between 30 and 70 Hz has been carried out on the data to be able to include all these peaks for further analysis and comparisons and to avoid the possible artifacts induced by narrow band filtering.

Figure 3 shows the power spectra of the grand average pre-stimulus EEGs (left column) and the AFCs of the grand average EPs (right column) of seven cats in four brain structures, to give a general idea of the frequency domain transformation of the data. Even though the gamma band peaks occurred in different cats with different center frequencies, both the grand average power spectra of the pre-stimulus EEGs and the grand average AFC of the EPs show globally the mean effect of these gamma peakings.

Figure 4 shows the averaged evoked responses of seven cats in four brain structures — gyrus ectosylvianus anterior (GEA, auditory cortex), hippocampus (HI), formatio reticularis (RF), and acoustical vermis of the cerebellum (CE) — filtered in the gamma frequency range. All of the averaged responses demonstrate an enhancement in the gamma band activity following the stimulation, which shows the time-locked nature of the gamma response. The grand averages of all the experiments filtered in the gamma range are presented at the bottom of the illustration.

In Fig. 5, the superimposed gamma band filtered single sweeps of one cat in four structures is shown. An evident time locking of the gamma responses in single sweeps to the stimulation time point can also be observed by superimposition of single sweeps.

Figure 6 shows the superimposed broad band filtered (1 - 70 Hz) and gamma band filtered (30 - 70 Hz) averaged responses of one cat in four brain structures. The gamma band components of the evoked responses are also clearly visible in the broad band filtered signals, which is evidence that we are not dealing with filter artifacts.

The statistical test results of the gamma enhancement in averaged evoked responses in all four structures are given in Table 1. The main effect of the factor "stimulation" (pre- and post-stimulus gamma band amplitudes) was significant (F(1,6): 8.62, p<0.03), whereas the effect of the factor "lead" was not significant (F(3,18): 1.08, p=0.38). Also, the interaction for the maximal amplitude measurements between "stimulation" and "lead" was not significant (F(3,18): 1.01, p=0.41). The mean values of the maximum gamma band amplitudes in pre- and post-stimulus periods are given in Fig. 7 in histogram form, with mean percent increase.

Discussion

Auditory gamma band responses are
The superimposed gamma band (30-70 Hz) filtered single sweeps of an AEP recording of one cat (upper row) and the gamma band filtered average AEPs of the same cat (bottom row) in different brain structures.

The broad band (1-70 Hz, thin line) and gamma band filtered (30-70 Hz, thick line) averaged auditory EPs of a representative cat in four brain structures. An extremely prominent gamma band response can be observed in cerebellum.

distributed in different brain structures (not only cortical but also subcortical)

There is a significant amplitude enhancement in the gamma band filtered averaged auditory responses of the cat auditory cortex in approximately first 100 ms after stimulation. The enhancement of the amplitudes of gamma band activity upon auditory stimulation is the sign of the phase-locking of this frequency component in single sweeps. The phase-locking effect can also be seen in superimposed gamma band filtered single sweeps. This type of early, phase-locked gamma response can not be seen, neither in the responses of cat visual cortex to moving stripes [8, 9, 11, 23, 24] nor in the recordings from the olfactory bulb of rabbits [22, 48, 52, 53] during stimulation with olfactory stimuli. The early auditory gamma response observed in the auditory cortex of the cat brain is time-locked to the stimulus and seems to resemble the gamma band response in human scalp recorded auditory evoked potentials.

Furthermore, the auditory gamma band response is not only observed in the auditory cortex, but can also be measured in different brain structures, such as reticular formation, hippocampus and cerebellum — both in averaged responses and in superimposed single sweeps. According to Basar’s “excitability rule” [1], reticular formation, hippocampus, or cerebellum, as well as the auditory cortex could respond in the gamma band to stimulation because the spontaneous electrical activities of all these structures show peaks in this frequency range (see Fig. 3).

Functional Interpretations on the Gamma Band Activity

Based on the excellent classification of Galambos [37], we will review the various gamma band phenomena in the literature to be able to interpret our results in a general context. Thereby, we will use the terminology Galambos introduced to differentiate temporal characteristics of the rhythm, as the latency and phase-locking of the rhythm to an event or its spontaneous nature.

Gamma Band Induced Rhythm in Olfactory Perception

The first studies on the gamma band activity of the brain began with Adrian [21], who reported that the application of odoriferous substances to the olfactory mucosa gave rise to a train of sinusoidal oscillations lasting for the duration of the stimulus. The “induced activity” was usually between 30 and 60 Hz. Later, Lavin, et al., [54] and Hernandez-Peon, et al., [55] stated that the 40 Hz activity could be elicited by a wide range of nonolfactory stimuli, and that this activity reflects the state of sensory stimuli rather than the activity triggered by olfactory processes.

Freeman (1975) emphasized that the 40 Hz wave packet has a key function in percepts of models in the olfactory bulb of the rabbit. Freeman [22] and Freeman and Skarda [53] have shown that the EEG of the olfactory bulb and cortex in awake and motivated rabbits and cats shows a characteristic temporal pattern consisting of
bursts of 40-80 Hz oscillations, superimposed on a surface negative baseline potential shift synchronized to each inspiration. According to Freeman, the neural activity that is induced by an odor during a period of learning provides the specification for a neural template of strength connections between the neurons made active by that odor. Subsequently, when the animal is placed in the appropriate setting, the template may be activated in order to serve as a selective filter for search and detection of the expected odor [48].

**Gamma Band Induced Rhythm as a Mechanism of Feature Linking in the Visual Cortex**

Recently, Gray and Singer [8, 10] have reported that neurons in the cat visual cortex exhibit oscillatory responses in the frequency range of 40-60 Hz. These oscillations occur in synchrony for cells located within a functional column and are tightly correlated with local oscillatory field potentials. Later, Gray and Singer [9] provided evidence that neurons in spatially separate columns synchronize their oscillatory responses, depending on the spatial separation and orientation preference of the cells. This mechanism was proposed to be a way of establishing relations between features in different parts of the visual field. Eckhorn, et al., [11, 23, 24] also found stimulus-evoked resonances of 35-85 Hz throughout the visual cortex when the primary coding channels were activated by their specific stimuli. The researchers raised the question whether coherent oscillations do indeed reflect a mechanism of feature linking in the visual cortex?

**Evoked Gamma Band Response**

In various studies of Basar, et al., [1, 18] and in a recent study of Galambos [37], it is shown that the auditory and visual transient evoked responses recorded from the human scalp contain a train of short latency wavelets in the gamma frequency range, precisely time locked to the stimulus and lasting approximately 100 ms. Recently, Pantev, et al. [44], discovered a gamma band transient magnetic oscillatory response, evoked in the human brain by the onset of auditory stimuli, consisting of four or more cycles locked in phase to stimulus onset in approximately the 20-to 130-ms poststimulus interval. Furthermore, Basar, et al., [18] showed a close relationship between the gamma band activity of the brain and the middle latency auditory evoked response. "The wavelet complex P25, N50, P60 seems to represent modulation of the 40 Hz mechanism. The wavelets of this complex are minima and maxima of the same oscillation, namely of the resonating 40 Hz wavepacket." The same viewpoint is supported by Makeig and Galambos [56] and Galambos [37]. The authors reported that the MLR is derived directly from the auditory gamma band response: "As the interstimulus intervalshortens with rise in stimulus rate, the gamma band response wavelet sequence begins to overlap on itself; at 10-Hz stimulation rate this overlapping process produces the MLR." The authors furthered their results in interpreting the steady state auditory evoked responses (SSR) as the overlapping of gamma band activity at higher stimulation rates than 10 Hz. Similarly, Regan [43] recorded an increased EEG energy in the 30 to 50 Hz region, when he stimulated subjects with light flickered at different rates. The author called it a "high frequency system."

**Emitted Gamma Rhythm**

Recently, Bullock, et al. [27], showed 15 to 25 Hz oscillations in the retina, optic nerve, and midbrain of the fish, which are approximately time-locked to the moment an omitted flash stimulus was due in an omitted stimulus paradigm. Prechtl & Bullock [57] extended these results to reptiles. By using a similar paradigm in humans, "high frequency omitted stimulus potentials" (6-40 Hz) were recorded [58]. Basar, et al., [26] and Basar-Eroglu and Basar [59] recorded from human scalp and from cat hippocampus a compound P300-40 Hz response in an omitted stimulus paradigm. Basar and Özesmi [46] and Basar and Ungan [15] determined the hippocampal frequency characteristics with macroelectrodes and found the existence of selectivities around theta (3-8 Hz), alpha (8-14 Hz) and gamma (30-50 Hz) frequency ranges. Leung [60] confirmed the existence of the gamma response in hippocampus. Vanderwolf, et al., [61] have shown a fast activity of 20 to 70 Hz

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### Table 1. Results from 2-way Analysis of Variance (stimulation x lead) for the maximal amplitudes of the gamma band activities

<table>
<thead>
<tr>
<th>Factor (df)</th>
<th>F</th>
<th>p</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stimulation (1,6)</td>
<td>8.62</td>
<td>0.03</td>
</tr>
<tr>
<td>Lead (3,18)</td>
<td>1.08</td>
<td>0.38</td>
</tr>
<tr>
<td>S x L (3,18)</td>
<td>1.01</td>
<td>0.41</td>
</tr>
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7. The mean values of the maximum peak-to-peak amplitudes of the gamma band activity in pre- and post-stimulus periods of averaged auditory responses recorded in GEA, RF, HI and CE. The increases of the amplitudes in the post-stimulus period are given as the percent of the pre-stimulus amplitudes on top of the bars. The amplitude enhancement due the stimulation is significant over all leads (p<0.03). The differences between the gamma amplitude enhancements in different locations are not significant.

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in hippocampus, which increases in power during voluntary behavior, as compared with automatic behavior.

Evoked Gamma Rhythm as a Rostrocaudal Scan in Human Brain

The studies of Limbás and Ribary [45] and Ribary and Llinás [62], on the auditory system in humans, using the MEG technique, indicate synchronized 40-Hz oscillatory activities over large cortical areas. The spatiotemporal pattern of this activity suggests the presence of a coherent rostrocaudal sweep of activity repeating every 12.5 ms due to a continuous phase shift over the hemisphere. "The findings indicate the presence of a scanning-like process most probably of intrinsic origin that covers much of the brain surface with a focus on the activated sensory area."

Spontaneous Gamma Rhythm in Thalamocortical System

Steriade, et al., [63] showed that the thalamic-projecting mesopontine cholinergic neurons have high firing rates (20 Hz) and tonic discharge patterns during brain arousal, with most interspike intervals concentrated between 20 and 40 ms. Furthermore, subpopulations of thalamocortical neurons have been found to display spontaneous fast prepotentials leading to full action potentials at slightly depolarized levels, in the frequency range of 25 to 45 Hz. Curró Dossi, et al., [64] demonstrated the doubling of the power of cortical waves around 40 Hz after the stimulation of the brain stem peribrachial area. According to Steriade, et al., [65] fast oscillations in the cortex might result from interactions in resonant cortical and thalamic networks under the facilitatory influence of the brain stem cholinergic input: "This virtually ubiquitous presence of 40-Hz oscillations over the neocortex then makes probable that the significance of such fast rhythms transcends the function of associative mechanisms between columns in particular sensory receiving areas."

Spontaneous Gamma Rhythm as an Index of Focused Arousal

The ongoing 40 Hz rhythm has been further interpreted as indexing a focused state of cortical arousal [41, 66]. According to Sheer [41], focused arousal is a hypothetically construction, one functional component of a complex attention process, which represents an interaction of ascending cholinergic brain stem reticular projections contingent with specific sensory inputs and/or memory traces at the cortex. This component can be directly measured in a narrow frequency band (36-44 Hz) of EEG from the intact scalp of both animals and human. Furthermore, the 40 Hz activity was hypothesized to be an index of the focused arousal in motor programming and that it represents an optimal periodicity for maximal synaptic transmission in cortical circuits [42].

Gamma Band Activity: a General Phenomenon of the Brain

The above examples and the present study show that gamma band activities exist in a number of brain structures of different species, with seemingly different functional/behavioral correlates. Activity could be recorded over the whole neocortex (MEG recordings in human and animal studies), thalamic nuclei, reticular formation, hippocampus, cerebellar cortex, retina, optic nerve, and midbrain.

Neurons with intrinsic membrane characteristics giving rise to gamma band oscillations, or neural networks with synaptic time constants optimal for gamma band oscillations seem to be distributed over a wide range of brain structures. This rhythm has also different dynamics in various structures and under different experimental conditions: it exists spontaneously and/or can be evoked, induced or emitted with different latencies and relations to sensory-cognitive events.

Furthermore, an important point demonstrated by the present study is that the gamma band response may exist in parallel (simultaneously) in many subsystems of the brain. Therefore, any interpretation on the functional significance and generators of this activity, based on observations in any one of these subsystems, seems not to be general enough. An integrative approach to diffuse gamma band activities of the brain seems to be more explanatory and fruitful.

Diffuse Gamma-Response System

We postulate a generalized concept of the brain as a distributed parallel processing system, in a wide framework of results with various species, brain structures and experimental conditions. We can thus state, tentatively, that the gamma band rhythm is an important universal operator in brain function, and is distributed to many subsystems of the brain. Edelman [67] states: "In such systems, integrative functions may emerge from the dynamics of the entire network rather than from linear computations performed at each nodal point in the circuit."

Goldman-Rakic [68] — in search for a topography of cognition — suggests that "it may be more useful to study the cortex in terms of information processing functions and systems rather than traditional but artificially segregated sensory, motor, or limbic components and individual neurons within only one of these components." We suggest that the resonating loops between different brain structures and the rhythms common to several subsystems establish links between anatomically distant but functionally complementary structures. The diffuse gamma system seems to be one important example of this type of linking; with the term diffuse describing the distributed nature of the gamma response in the brain. We have already introduced the concepts of distributed alpha, theta and gamma response systems [5, 26, 31, 69]. At this level of investigation, it is not possible to define the connections between the elements of these systems by neuron to neuron tracking, or to define the directions of signal flow and exact boundaries of neuronal populations involved. However, rhythmic phenomena in these frequency ranges are not unique features of the observed single subsystem of the brain, and their simultaneous existence in distant brain structures may be a relevant and important point in understanding cooperative activities.

Beyond this concept, finer analysis and functional interpretation of specific examples of gamma activities may be necessary. However, such findings should be considered as a part of the distributed gamma response system of the brain. While loosely time-locked 40 Hz response is recorded in the sensory cortex, or a tightly time-locked gamma band activity is recorded over the whole neocortex, then
it should be asked: What mechanism allows the thalamic nuclei, hippocampus, reticular formation, and cerebellar cortex to respond in this frequency range at the same time?

We tentatively conclude that the gamma band activity is one of the common language elements of the brain. It may play a role in the information transfer between subcomponents of the brain, as also do a number of other oscillatory activities such as alpha, theta or beta rhythms.

Rhythmicities as Building-Blocks
According to our hypothesis, spontaneous EEG rhythmicities — probably due to hidden sources or induced rhythmicities — appear during various types of behavioral and sensory or cognitive conditions. Accordingly, we consider such various rhythmic activities in several parts of the brain as "building blocks" [30] which accompany physiological and psychological events. Only their combination should be considered as a representation of complex behaviour. Further, only in special cases of simple behaviour in which the brain has a state of high cooperation or synergy, is it possible to isolate rhythms with a unique frequency.

Conclusion
Several paradigms or strategies — some of them introduced in this article — were applied to point out that the EEG serves as a functionally relevant signal (or operator) in various frequency channels. These can be brought to resonant behavior depending on functional brain states. We emphasize that the EEG-operators are functionally significant if 1-4 Hz, 4-7 Hz, 8-13 Hz, or 40 Hz activities can be brought to a resonant state with a high degree of synchrony. The time-locking of an internally induced EEG fragment may depend on the specific behavior (for example induced alpha templates prior to a cognitive target, 40 Hz induced rhythmicities with 300 ms latency in hippocampus during cognitive tasks). For topographic aspects see, e.g., Schürmann & Basar [34] and Basar & Schürmann [35].

We assume that the analysis of EPs performed within the scope of resonance phenomena and/or induced rhythmicities can be developed into a most important tool to understand and to interrelate sensory and cognitive functions of the brain. Once the physiological significance of 10 Hz and 40 Hz resonance phenomena is established, the type of component analysis here presented provides, we believe, an excellent possibility to describe functional states of the intact brain during consciousness. We assume that by using such methods, the analysis of EEG, sensory EPs, and event-related potentials will experience a renaissance in functional brain research.

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Erol Basar is professor of biophysics and physiology and is at present the head of the Neurophysiology Research Group at the Medical University of Lübeck. Dr. Basar is honorary president of the Brain Dynamics Unit of the Turkish Research Council in Ankara. He studied at the universities of Munich and Hamburg and was physiology-instructor between 1965-68 at Hanover University. Dr. Basar was awarded his Ph.D. degree at the Medical University of Lübeck. Dr. Basar was a research fellow at the Institute of Physiology of Medical University of Lübeck, Germany, in 1989. Since 1991 he is associate professor at the department of Physiology of Istanbul Medical Faculty, and since 1992 he is the director of the Electro-Neuro-Physiology Research and Application Center of Istanbul University. He is also associated with the Brain Dynamics Research Unit of the Turkish Scientific and Technical Research Council. His current research interests are brain electrophysiology and the sensory and cognitive functions of the brain.

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Dr. C. Basar-Eroğlu was born in 1950 in Ankara, Turkey, where she received her M.Sc. degree in biology and Ph.D. degree in biophysics at the Hacettepe University of Ankara. In 1992 she was awarded the venia legendi at the Medical University of Lübeck.

Dr. Basar-Eroğlu is a psychophysicologist at the Institute of Psychology and Cognition Research, University of Bremen, Germany. Her current research activities focus on the electroencephalogram, event-related potentials, cognitive processes of the brain and multisensory perception.

Tamer Demiralp was born in Istanbul, Turkey, on February 4, 1963. He received the M.D. degree from the Istanbul Medical Faculty of Istanbul University in 1986. He was trained in Physiology in Istanbul Medical Faculty. He received an M.S. degree in biomedical sciences at the Biomedical Engineering Institute of Bogaziçi University in Istanbul. He was a research fellow at the Institute of Physiology of Medical University of Lübeck, Germany, in 1989. Since 1991 he is associate professor at the department of Physiology of Istanbul Medical Faculty, and since 1992 he is the director of the Electro-Neuro-Physiology Research and Application Center of Istanbul University. He is also associated with the Brain Dynamics Research Unit of the Turkish Scientific and Technical Research Council. His current research interests are brain electrophysiology and the sensory and cognitive functions of the brain.

Martin Schürmann, M.D. was born in Bottrop, Germany, in 1962. He received the degree of "Dr. med." from the Rheinisch-Westfälische Technische Hochschule Aachen, Germany, in 1988. From 1988 to 1989 he worked in the Department of Neuroanatomy at the Rheinisch-Westfälische Technische Hochschule Aachen, Germany. In 1989 he joined the neurophysiology group at the Institute of Physiology, Medizinische Universität zu Lübeck, Germany. He is currently working in the field of EEG and evoked potential analysis with respect to functional roles of evoked EEG rhythms in sensory and cognitive processing.
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