Enhanced phase synchrony in the electroencephalograph γ band for musicians while listening to music

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Multichannel electroencephalograph signals from two broad groups, 10 musicians and 10 nonmusicians, recorded in different states (in resting states or no task condition, with eyes opened and eyes closed, and with two musical tasks, listening to two different pieces of music) were studied. Degrees of phase synchrony in various frequency bands were assessed. No differences in the degree of synchronization in any frequency band were found between the two groups in resting conditions. Yet, while listening to music, significant increases of synchronization were found *only* in the γ-frequency range (>30 Hz) over large cortical areas for the group of musicians. This high degree of synchronization elicited by music in the group of musicians might be due to their ability to host long-term memory representations of music and mediate access to these stored representations.

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A major focus of the study of neuroscience is synchronization between neurons, ranging from individual neurons to neuronal assemblies, within one or several areas of the brain [1]. Any cognitive or higher information processing task is invariably associated with the activation and cooperation of immense numbers of neuronal assemblies widely distributed over the cerebral cortex [2]. Although modern imaging studies are found to be extremely popular and useful in the localization of brain functions [3], they are not ideally suitable to detect cooperation among physically distant cortical areas. Electroencephalogram (EEG) or magnetoencaphalogram signals have the potential to assess higher brain functioning especially when the measurement of the degree of synchronization is of primary concern [4]. In general, an EEG signal involves a state-dependent mixture of local (more dominant functional segregation) and global (more dominant functional integration) processes and is a reflection of cortical neuronal assemblies showing a high degree of in-phase synchronized firing [5]. Local phase synchrony can be detected with microelectrodes by computing cross correlograms between spike discharges [1]; global interaction has been shown to exist in the EEG [4]. Recently, single-unit evidence for phase locking of oscillatory responses between widely separated cortical regions has also been reported [6]. These findings led to the hypothesis that phase synchrony might provide a platform for binding together different sensory attributes and for large-scale cognitive integration [7].

Detection of synchrony between two cortical regions from EEG signals is not trivial. It requires methods that are different in principle from the correlation analysis applicable to microelectrode studies. The popular way to detect synchronization from multichannel EEG signals is coherence, which measures the degree of linear association in the frequency domain. The coherence function finds many useful applications in cognitive studies [4,8], but the results based on coherence depend on several factors like stationarity of the signal, segment length, number of segments, and reference electrodes, to name only a few [9–11]. Since determining phase synchronization between two electrodes is sufficient to infer whether the two cortical regions interact, we applied a different approach to measure the degree of phase synchrony, which was found to be useful for nonstationary neurophysiological signals [12].

Music plays a very important and universal role in our culture across races and countries. Yet music perception is a complex cognitive process involving different brain structures dependent on various factors such as the type of musical stimulus, musical experience, mode of listening, etc. [13,14]. Music, like other forms of expression, requires specific skills for its perception and production. Both the organization and representation of these skills in the human brain are far from being understood. In this paper, we address this problem by comparing the degree of phase synchrony in EEG signals between musicians and nonmusicians while they were attentively listening to different musical pieces. The same type of analysis was performed during resting conditions. Phase synchrony was measured for different standard frequency bands, which may reflect functionally different components of information processing [15].

Here, we briefly summarize the essential facts related to phase synchrony and refer the interested reader to Ref. [16] for detailed discussions. For two mutually coupled periodic oscillators, the phase dynamics can be formulated as

$$\frac{d\phi_1}{dt}=\omega_1+\eta_1 f_1(\phi_1,\phi_2), \quad \frac{d\phi_2}{dt}=\omega_2+\eta_2 f_2(\phi_2,\phi_1), \quad (1)$$

where $\phi_{1,2}$ are the phases of two oscillators, the coupling terms $f_{1,2}$ are 2π periodic, and $\eta_{1,2}$ are the coupling coefficients. The generalized phase difference or relative phase is defined as

$$\Phi_{m,n}=m\phi_1-n\phi_2\equiv m\omega_1-n\omega_2+\eta F(\phi_1,\phi_2), \quad (2)$$

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where $F(\cdot)$ is also 2π periodic. Generally, phase locking requires $|m\phi_1(t)-n\phi_2(t)-\epsilon|<\text{const.}$, where ϵ corresponds to the average phase shift. Since in the present study signals came from the same physiological system, i.e., the brain, only 1:1 synchronization was considered here; thus $m=n=1$ and they are dropped for clarity. It is to be noted that even for the synchronized state the relative phase Φ is not constant but oscillates around ϵ, and this oscillation ceases if the coupling function F depends on Φ only.

For noise-free coupled oscillators, phase synchrony is synonymous with frequency locking, but this is not the case for coupled noisy and/or chaotic systems. Recently, it has been shown [17] that, for coupled chaotic systems, the irregular amplitudes affect phase dynamics in a similar fashion as noise; thus, both types of system can be treated within a common framework. For weak noise, Φ is not constant but slightly perturbed; phase slips of $\pm 2\pi$ occur and Φ is stable only between two phase slips [18]. Thus, the relative phase $[\Phi(t)]$ is unbound and the distribution of $\Phi(t) \bmod 2\pi$ becomes smeared, but nevertheless unimodal. For strong and unbound noise (i.e., Gaussian noise), phase slips occur in an irregular manner, so only short segments of nearly stable phase are possible and the relative phase difference series performs a random walk [17]; thus, the region of synchronization is smeared and phase synchrony can be detected only in a statistical sense [12].

To quantify the degree of phase synchrony between two signals $\{x_{1,2}(t)\}$, the procedure [12] comprises the following steps: (i) compute the instantaneous phases ϕ_i $(i=1,2)$ of each signal by the analytic signal approach using the Hilbert transform [9], $\phi_i(t)=\tan^{-1}\{(\int_{-\infty}^{\infty}[x_i(\tau)/\pi(t-\tau)]d\tau)/x_i(t)\}$, (ii) find the relative phase $\Phi=|\phi_1-\phi_2|$, (iii) obtain the distribution function of $\Phi \bmod 2\pi$ by suitable partitioning, and finally (iv) compute the index $\rho=(H_{max}-H)/H_{max}$, where H is Shannon's entropy of the distribution function, and $H_{max}=\ln P$ with P the number of partitions. The degree of phase synchrony increases monotonically with ρ [19]. The primary substrate of synchrony in neuronal populations is the existence of groups of neurons interconnected by mutual excitatory and inhibitory synaptic connections [5]. Thus, if ρ between two signals coming from two electrodes is high, the functional cooperation manifested by the synaptic connections between large populations of neurons in the associated cortical regions will also be high.

In this study, 20 male subjects were included: musicians (10 subjects with mean age of 25.7 yr with at least 5 yr of musical training) and nonmusicians (10 subjects with mean age of 25.4 yr without any musical training). EEG signals were recorded from 19 electrodes placed according to the International 10/20 placement system [20]. Average signals of both earlobes were used as reference [21]. All subjects were instructed to listen attentively for several minutes via earphone to music (a piece of computer music by G. Martin, and the sonata for violin and piano by Beethoven op. 12/1). The total duration of each musical piece was 90 s. EEG's were also recorded in resting conditions, with eyes opened and eyes closed, before, between, and after each musical task. Their durations were the same as those of the musical pieces that were played. The sampling frequency was 128 Hz and the analog-to-digital precision was 12 bit.

First, signals were detrended by fitting a polynomial of second order and were divided into six frequency bands: δ (0.025–4 Hz), θ (4–7 Hz), α (7–13 Hz), β (13–30 Hz), and γ (30–50 Hz). A sixth order IIR Butterworth filter was used for band-pass filtering. For each filtered signal, a nonoverlapping window of 6 s duration was used and, for each window, values of ρ were measured considering all possible combinations between the 19 electrodes. To compare the degrees of phase synchrony between the two groups of subjects, a normalization procedure was carried out to obtain synchrony values comparable between near and distant electrode pairs. Given ρ_{ij} (ρ for electrode pair i and j), let μ_{ij} and ν_{ij} be the mean and variance computed from the set of nonmusicians; the relative phase synchrony values are computed as $\sigma_{ij}=(\rho_{ij}-\mu_{ij})/\sqrt{\nu_{ij}}$. If $\sigma_{ij}\geqslant 2.33(\leqslant -2.33)$, it can be inferred that the degree of phase synchrony between electrode pair i and j was significantly higher in musicians than nonmusicians (or in nonmusicians than musicians, respectively).

Figures 1(a) and 1(b), respectively, show the comparison, expressed in terms of σ, between eyes closed and eyes opened conditions. In both conditions, no significant differences were found in any frequency band in the degree of phase synchrony between musicians and nonmusicians. Figure 2(a) shows the profile of relative synchrony while both groups were listening to computer music. The most striking feature is the clustering of all frequency bands except γ. Further, only the synchrony in the γ band turned out to be significantly higher for musicians than nonmusicians. This enhanced synchrony was found in many cortical regions. Figure 2(b) shows the same profiles while listening to Beethoven, which produces qualitatively similar results with the values of σ varying slightly topographically from those while listening to computer music.

To approach the question of possible hemispheric dominance during musical tasks, mean values of ρ obtained by averaging over all possible electrode combinations within each hemisphere were plotted with time in Fig. 3. While listening to both pieces of music, musicians showed clear left-hemisphere dominance throughout the entire time course of both pieces (listening to computer music, Mann-Whitney rank sum test [22] $Z=4.46$, probability value $p<0.001$; listening to Beethoven, $Z=3.80$, $p<0.01$). On the other hand, in nonmusicians, right-hemisphere dominance was found. No significant differences in phase synchrony were found during resting conditions.

The special role of the γ-band synchrony in musicians while listening to music demands further attention. Musical training on any instrument not only improves manual skill of both hands but also increases the ability to discriminate different sounds and to mentally follow and reconstruct acoustic architechtonic structures. Any complex music (like those considered in this study) is interwoven with a variety of acoustic features such as pitch, loudness, timbre, melodic and harmonic structure, rhythm, etc., in an intricate way. Musicians, certainly, have greater abilities to characterize these different elements than nonmusicians. Considering the crucial role of oscillations in the γ band in binding several

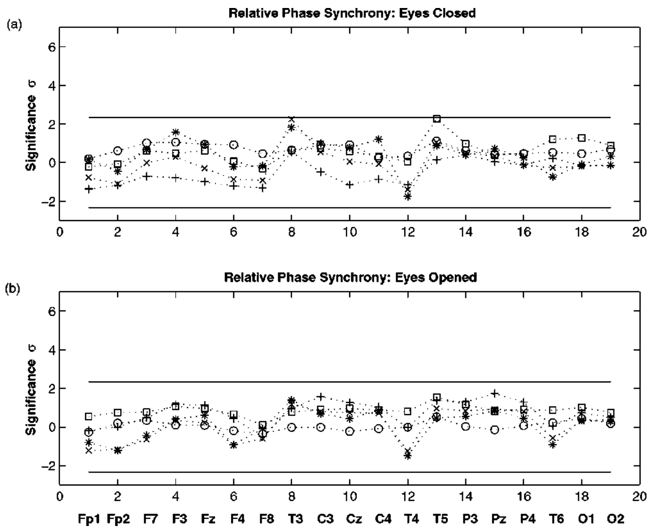

FIG. 1. Phase synchrony for 10 musicians relative to 10 nonmusicians in terms of σ in resting conditions: (a) eyes closed, (b) eyes opened. Results (averaged over windows, subjects within each group, and for all possible combinations for each electrode) are shown in five frequency bands: δ (marked by ○), θ (marked by □), α (marked by +), β (marked by ×), and γ (marked by *). Horizontal lines ($\sigma = \pm 2.33$) denote the 99% significance level; any value above the upper line indicates significantly higher degrees of phase synchrony in musicians than nonmusicians, and any value below the lower line indicates higher phase synchrony in nonmusicians. In resting conditions, the two groups are not different in terms of synchrony.

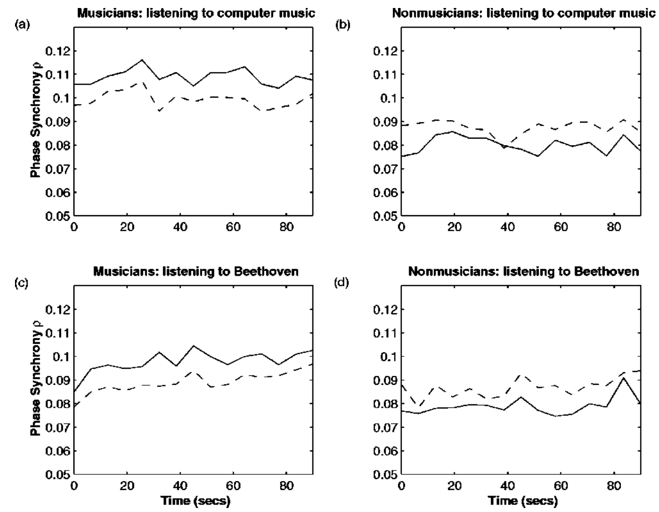

FIG. 3. Temporal variations of phase synchrony in the γ band while listening (a) and (b) to computer music and (c) and (d) to Beethoven for (a) and (c) musicians and (b) and (d) nonmusicians. Results were averaged over all subjects within each group and all possible electrode combinations as follows: within left hemisphere (solid line), within right hemisphere (dashed line). In musicians, the left hemisphere presents higher phase synchrony than the right one; in nonmusicians, the right hemisphere is found to be slightly dominant in the degree of phase synchrony.

features into a single perceptual entity as reported earlier [1,23], these higher abilities for discriminating different acoustic features can be surmised as one reason for the high synchrony for musicians in the γ band, which is supposed to integrate the information associated with these various acoustic features in a dynamical fashion [24]. Further, attentively listening to any music is always connected to anticipation, which is based on much musical experience. During listening to music, in musicians, an extensive retrieval of stored musical patterns from the memory takes place. This is another possible reason for the high synchrony over distributed cortical regions. The question of asymmetry between the two hemispheres for listening to music is extremely complex and has been a matter of discussion for many years. Today the general assumption on the lateralization of musical abilities, derived mainly from studies on amusias, focuses on the view that right-sided brain lesions mainly disturb the melodic and left-sided the rhythmic aspects of musical sequences [25]. The asymmetry, as reported here, in the functioning of the two hemispheres for musicians was also established anatomically [26], where the planum temporale was found to be larger in the left brain in musicians. Moreover, it has also been found from brain damaged patients that the left side of the brain is better equipped for hosting long-term memory representations of music [27].

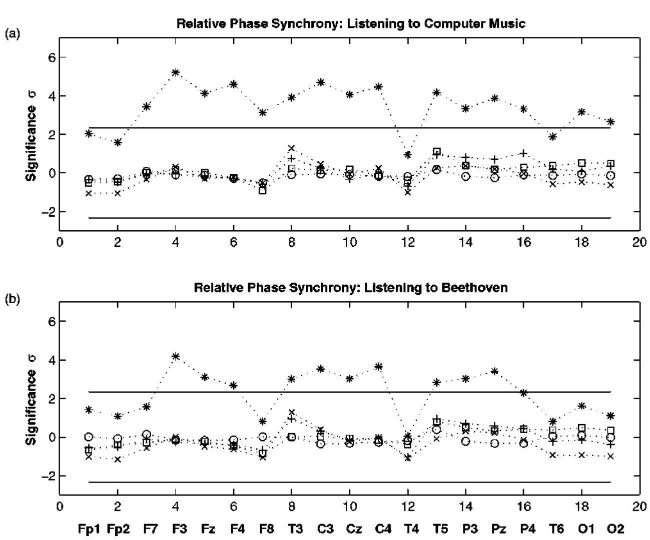

FIG. 2. Phase synchrony for musicians relative to nonmusicians in terms of σ while listening to two different pieces of music: (a) computer music by G. Martin, (b) Beethoven op. 12/1. Results were averaged as in Fig. 1 (see legend of Fig. 1 for identification markers of different frequency bands). In both cases, phase synchrony was significantly higher for musicians and only in γ the range. Note that increases were found over multiple cortical areas.

A few critical remarks may be raised. First, it is well known that the γ band has much smaller amplitude than the α or θ band and is therefore masked by these larger-magnitude oscillations. Digital filtering and time-frequency distribution based on wavelet transform are frequently used for extracting the high-frequency low-amplitude γ-band activity [28]. Wavelet based decomposition is ideally suitable for single-trial data, whereas in the present study music has been treated as a continuous input for the entire recording duration. Thus, the adopted scheme of filtering seems appropriate assuming that the γ band represents a distinctive brain state, which can be operationally distinct and separable, even though the complete brain may be simultaneously active in other modes. Secondly, the γ oscillation can be contaminated by various possible artifacts, mostly by muscles. Yet muscle spectra are very broadband and it is known that muscle activity affects all frequencies above α, but in this study not even in β were any differences between the two groups found in their degrees of phase locking. Further, the enhanced γ-band synchrony for musicians was still present when temporal electrodes were excluded from the analysis. Thus, these results tend to exclude muscle activity as an explanation for these findings. Thirdly, the chosen α band may be criticized as too broad, since there are many reports showing that the upper and lower α bands play different roles in different cognitive states [29]. Therefore, to probe the role of different α bands, we divided α into three bands: $\alpha1$ (7–9 Hz), $\alpha2$ (9–11 Hz), and $\alpha3$ (11–13 Hz), and repeated the whole study of phase synchrony for these three bands for both groups. No significant differences were found with respect to any of these α bands (figures not included for brevity). It should be noted that these comparisons were always made between two groups of subjects performing the same tasks but not between different tasks within each group.

To summarize, musicians' brains show significantly high phase synchrony in the γ band as compared with nonmusicians' brains. This enhancement most likely is elicited by music because no differences were found between the two groups at rest. Strangely, this significant increase of synchrony was found only in the γ band. Finally, the paper demonstrates that musical training has significant impact on the degree of functional cooperation among multiple cortical regions and once more demonstrates the usefulness of noninvasive (and inexpensive) EEG in cognitive research.

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