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Scale-similar activity in the brain

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The spectral analysis of multichannel magnetoencephalographic data is presented. This analysis revealed a local similarity regime in brain activity (in more than two decades of frequencies) and provided new parameters for noninvasive experimental studies of the brain. [S1063-651X(97)50509-5]

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The study of systems with strong interactions of many degrees of freedom is one of the most important subjects in physics. Examples of these systems are turbulent flows of ordinary fluid and plasma, the global structure of the universe, and the unified theory of fields (superstrings). Turbulence is more accessible (analytically, experimental, and numerically) and its study can provide guidelines for the analysis of other systems. The nature of these systems and the mechanism of interaction can be quite different. However, in many of these systems we may expect characteristic cascade processes and a regime of scale similarity (see [1] and references therein).

The present Rapid Communication is a test of scale-similar activity in the brain. The human brain consists of about hundred billion neurons. Each neuron has up to ten thousand connections (for a description of the brain from a point of view of physics see recent works [2–5] and references therein). Neurons are assembled in a hierarchical structure, from a small group of neurons to larger groups, etc. A flux of activity in this hierarchy can produce a similarity regime.

Data for this study were obtained from the Scripps Research Institute (La Jolla, CA), using a dual probe 37-channel superconducting quantum interference device (SQUID; see [6] for details) magnetoencephalograph. We did an analysis of the measurements of the normal component of the magnetic field on the brain surface from 70 channels in the range from 0.1 to 115 Hz. A sketch of the relative positions of channels is presented in Fig. 1. The distance of each sensor from the skull is between 2 and 2.5 cm. The magnetometer was in a magnetically shielded room and the power of the environmental noise was, at least, one order of magnitude lower than that of the neural signals. Power-line interference (highly correlated and spectrally localized) was eliminated from the data.

The data presented here are from a healthy female (age 39) and a healthy male (age 38), both lying on their right side, while resting with their eyes closed. The data were recorded over 30 min with a sampling frequency of 231.5 Hz. The power spectra were calculated by the FFT method, averaging 50 intervals with 8192 points each.

The power spectrum of individual channels has peaks corresponding to typical brain rhythms [Figs. 2(a) and (b) and 3(a) and (b)]. However, when we took the spectrum of the difference between the signals of two channels, the peaks practically disappear in many cases and we obtained a similarity regime (power law) for, at least, two decades of frequencies [Figs. 2(c) and 3(c)]. The similarity parameters (α,β) and the error ε were determined by minimizing the mean square deviation

$$Q=\langle[\log F(\omega)-\alpha-\beta\,\log\omega]^2\rangle, \tag{1}$$

$$\varepsilon=\frac{Q^{1/2}}{\langle|\log F(\omega)|\rangle}, \tag{2}$$

where $F(\omega)$ is the power spectrum and brackets $\langle\rangle$ indicate averaging over the range of frequencies ω. The range in this presentation was from 0.4 to 40 Hz, but analogous results also hold for the ranges 0.2–20 and 0.5–50 Hz. The parameters $(\alpha,\beta,\varepsilon)$ were calculated for the spectra of 70 channels and for the spectra of signal differences for all 2415 pairs of channels. Let us denote $\{\}$ for averaging over all pairs of channels. The averaged parameters and rms deviations for the range 0.4–40 Hz are

$$\{\alpha_1\}=23.11,\sigma(\alpha_1)=0.856,\{\alpha_2\}=24.02,\sigma(\alpha_2)=0.913, \tag{3}$$

$$\{\beta_1\}=-0.980,\sigma(\beta_1)=0.158,\{\beta_2\}=-1.28,\sigma(\beta_2)=0.187, \tag{4}$$

$$\{\varepsilon_1\}=0.022,\sigma(\varepsilon_1)=0.0060,\{\varepsilon_2\}=0.026,\sigma(\varepsilon_2)=0.0070. \tag{5}$$

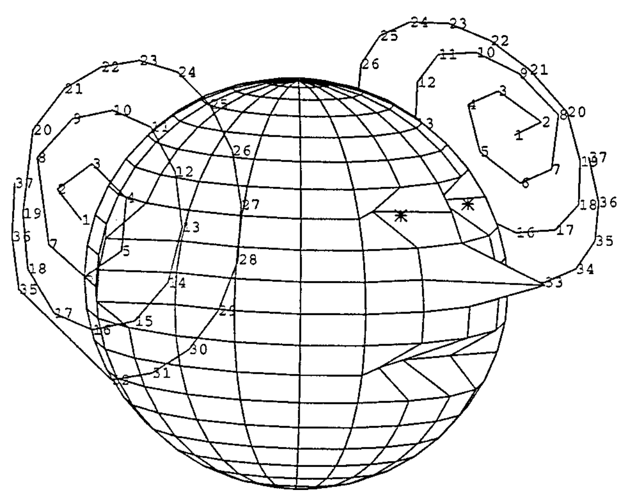

FIG. 1. Sketch of the positions of channels.

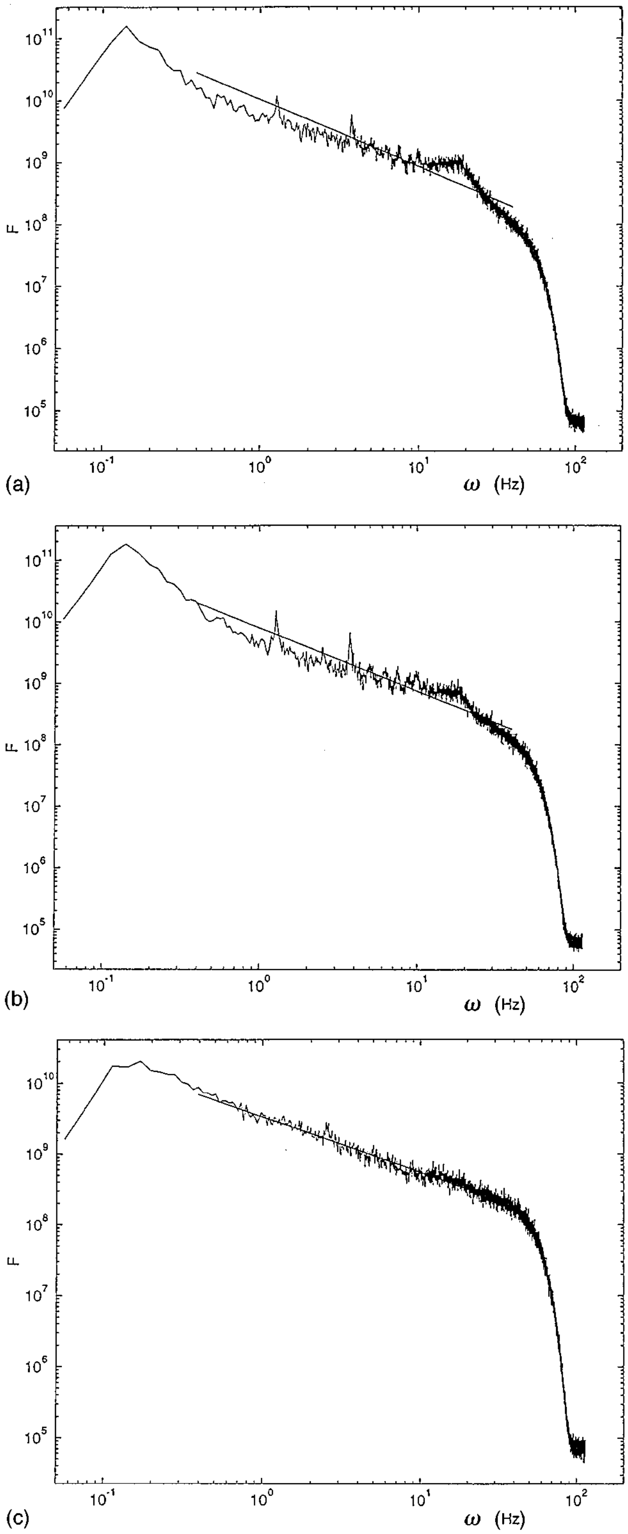

FIG. 2. Power spectra of second order $F(\omega)$ for the first subject (female): (a) R16 (channel 16 in the right hemisphere), $\alpha=23.1$, $\beta=-1.09$, $\varepsilon=0.0217$; (b) R32, $\alpha=22.8$, $\beta=-1.03$, $\varepsilon=0.0173$; (c) R16-R32 (signal difference), $r=2.4$ cm, $\alpha=21.9$, $\beta=-0.783$, $\varepsilon=0.008\,09$.

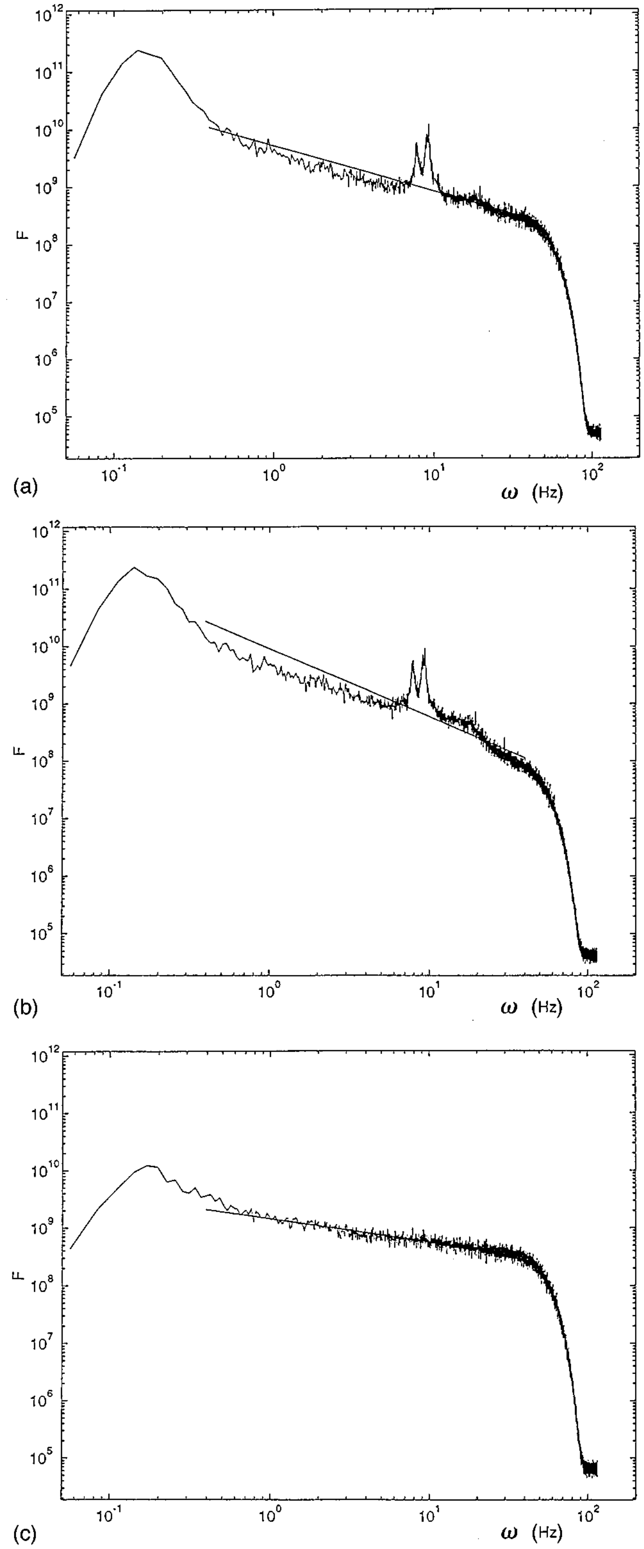

FIG. 3. Power spectra for the second subject (male): (a) L17 (channel 17 in the left hemisphere), $\alpha=22.4$, $\beta=-0.795$, $\varepsilon=0.0199$; (b) L34, $\alpha=22.9$, $\beta=-1.19$, $\varepsilon=0.026$; (c) L17-L34, $r=2.4$ cm, $\alpha=21.1$, $\beta=0.40$, $\varepsilon=0.007\,65$.

Here subscripts (1,2) indicate subjects (1, female; 2, male), $\sigma(\gamma)\equiv\{(\gamma-\{\gamma\})^2\}^{1/2}$ is the rms deviation for a characteristic γ, which can be α, β, or ε. For the range 0.2–20 Hz the averaged errors are $\{\varepsilon_1\}=0.015$, $\{\varepsilon_2\}=0.025$; for the range 0.5–50 Hz they are $\{\varepsilon_1\}=0.025$, $\{\varepsilon_2\}=0.026$.

The three-dimensional distances r between the positions of the sensors (channels) were from 2 to 21 cm. All pairs of channels were ordered with the increase of the distance be-

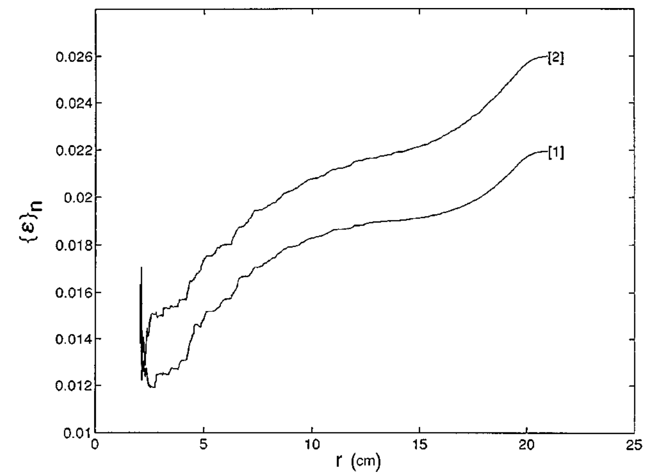

FIG. 4. Averaged error $\{\varepsilon\}_n$ as function of distance between channels r for both subjects (see text).

tween probes. We denote $\{\}_n$ the averaging over the first n pairs of channels. Figure 4 shows the global tendency of averaged error $\{\varepsilon\}_n$ to increase with the distance, but for some of the pairs of relatively close channels we still observed peaks in the spectra of the signal difference. Our interpretation of these data is that scale similarity is generally local, but there are some preferable regions in the brain (probably, functionally connected), for which scale similarity is more pronounced. The locations of some neighboring pairs of channels with relatively large ε may indicate the boundaries between such regions. We plan to use the parameters of scale similarity $(\alpha,\beta,\varepsilon)$ for a mapping of the brain and connect this mapping with anatomy and physiology. Similar data were taken from 18 other subjects. The spectral analysis of the data from several randomly chosen subjects was performed. All the data revealed the same phenomena of local scale similarity.

The similarity regime with even smaller errors was observed for the higher order moments of the signal difference. Particularly, for the same pairs of channels as in Figs. 2(c) and 3(c) and the same frequency diapason, the power spectrum taken from the square of the signal difference gives correspondingly $\varepsilon_1 = 0.004\,99$, $\varepsilon_2 = 0.005\,07$. For the cube of the signal difference we obtained $\varepsilon_1 = 0.003\,60$, $\varepsilon_2 = 0.004\,13$. This suggests the use of the infinitely divisible distributions [7,1] for the modeling of brain activity, which is an important subject for future studies.

To the best of our knowledge, the similarity regime for such local characteristics of brain activity has not been previously observed. Brain rhythms are apparently synchronized (at least in functionally connected areas) and play a role similar to coherent structures in turbulent flow. The signal difference between channels is analogous to the velocity increment between points in turbulence in the sense that both quantities correspond to local structure and reveal the similarity regime (see [8,9] and references therein).

From these results we can conclude that there is a local similarity regime in brain activity. We plan to study the similarity regime with a larger group of subjects and in greater detail, including additional channels and a wider range of frequencies. Corresponding distributions and similarity exponents may be important characteristics of brain activity, that reflect a hierarchical processing of information. They may serve as a diagnostic tool for certain mental disorders (this work is in progress and the results will be presented elsewhere).

After this work was completed, we became aware of the paper [10], in which a power law in the diapason from 20 to 40 Hz was mentioned for the spectrum of an individual channel. We had noticed a similar behavior of one-channel spectra in our data [Figs. 2(a) and (b) and 3(a) and (b)]. However, by standards of spectral analysis for the scale-similar phenomena, the diapason of doubling frequency is too narrow to assert that this is a similarity regime. Cross-power spectra were also presented [10] for two distances between channels. Notably, the coherence was smaller for the smaller distance, which may correspond to the boundary situation, discussed above. However, the spectrum of the signal difference between channels was not considered in [10].

Let us stress that the local similarity regime observed in this Rapid Communication (in more than two decades of frequencies), in our opinion, places spontaneous brain activity in the general framework of the scale-similar phenomena for systems with strong interactions. It also provides new parameters for noninvasive experimental studies of the brain.

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