Noise-Induced Entrainment and Stochastic Resonance in Human Brain Waves

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We present the first observation of stochastic resonance (SR) in the human brain's visual processing area. The novel experimental protocol is to stimulate the right eye with a subthreshold periodic optical signal and the left eye with a noisy one. The stimuli bypass sensory organs and are mixed in the visual cortex. With many noise sources present in the brain, higher brain functions, e.g., perception and cognition, may exploit SR.

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Noise plays a surprising role in biological systems [1,2]. Stochastic resonance (SR), which improves signal detection by superimposing noise, has been discovered in many sensors of living organisms [3–5]. Very recently, SR phenomena in more complex systems, such as human tactile sensing, neural networks of mammalian brains, and the blood pressure control system in the human brain stem, have been well established [6–13]. Thus far, however, there has been no study of SR for information processing systems in the human brain. Here, for the first time, we exploit the way in which the eyes are cross wired to the visual cortex to bypass sensory organs and observed SR in the human visual cortex itself. While brain wave entrainment by simply periodic stimuli has been well established as a phase-locking dynamics [14–16], we demonstrate SR and global noise-enhanced entrainment of the brain waves in an information processing area of the central nervous system.

In the human, there is a large variety of chaotic firing of neuron networks and columns that function as complex oscillators, as well as spontaneous electrochemical noises [17]. Such noisy signals provide internal noise sources to trigger SR phenomena in the brain. In addition, recently it has been known that spatiotemporal dynamics of brain wave entrainment is closely related to higher order brain functions [18–21]. Consequently, we anticipate SR could improve information processing related to cognition and perception.

Brain waves result from a summation of the postsynaptic potential (EPSP). Usually, they are detected on the scalp through various tissue layers between it and the brain, e.g., the skull, meninges, and cerebrospinal fluid. Nevertheless, brain waves appear to indicate rather local information of brain activity [22]. They are classified into five different waves based on their frequency range: typically, $\sim$8–13, $\sim$14–30, $\sim$30–60, $\sim$0.5–3, and $\sim$4–7 Hz, respectively, called α, β, γ, δ, and θ waves [23]. Of these, the α wave is considered to be a fundamental brain wave that appears when a human is in a rest state with closed eyes. The other brain waves, on the other hand, appear in an active situation of the brain, and are thought to be sensitive to mental, psychological, and physical diseases. Applying large amplitude periodic photic stimuli to the eyes can induce a collective firing of neurons synchronizing with the stimuli in many parts of the brain, i.e., entrainment of brain waves [14–16,24,25]. As a result, induced brain waves dynamics have been often used for clinical diagnoses [23].

During higher functional activities, the spatiotemporal dynamics of brain waves may change [21]. For example, in a cat study, synchronization of action potentials between areas of the visual and parietal cortex has been reported [20]. In the human perception process, the γ wave is globally synchronized in space and time [21]. This suggests that phase synchronization of brain waves may be evidence of neurons collectively firing in many different parts of the brain. Therefore, spatiotemporal entrainment and transient properties of brain waves (α, β, and γ waves) measured on the scalp are associated with cognition, language processing, and working memories [18,19,21]. As is well known, at an optimum noise intensity, SR enhances synchronization among many coupled oscillators [26–31]: The possibility emerges that a similar effect could occur in the synchronization of brain waves.

The measurements were performed on five healthy male students, 22 $\pm$ 2 years old. During measurements of their brain waves, the subjects were in a rest state with their eyes closed. The visual path for photic stimuli from eyes to the brain is shown in Fig. 1. A white color light panel was used as a source of external light stimulus to the eyes. Two panels were prepared as periodic and noisy light sources and placed 15 cm from the subject's eyes. The periodic stimulus was applied to the subject's right eyelid and the noisy stimulus to his left eyelid. The characteristics of the applied noise, Gaussian quasiwhite noise ranging from 15 to 60 Hz, are shown in Fig. 1. Electroencephalograms (EEGs) were recorded with a ten-channel electroencephalograph where each channel was assigned one of the ten electrode positions of the international 10–20 electrode method shown in Fig. 2. The data were simultaneously stored to the hard disk of a personal computer after analog-to-digital (AD) conversion. The sampling rate of 500 Hz was used with 12-bit resolution using an AD board.

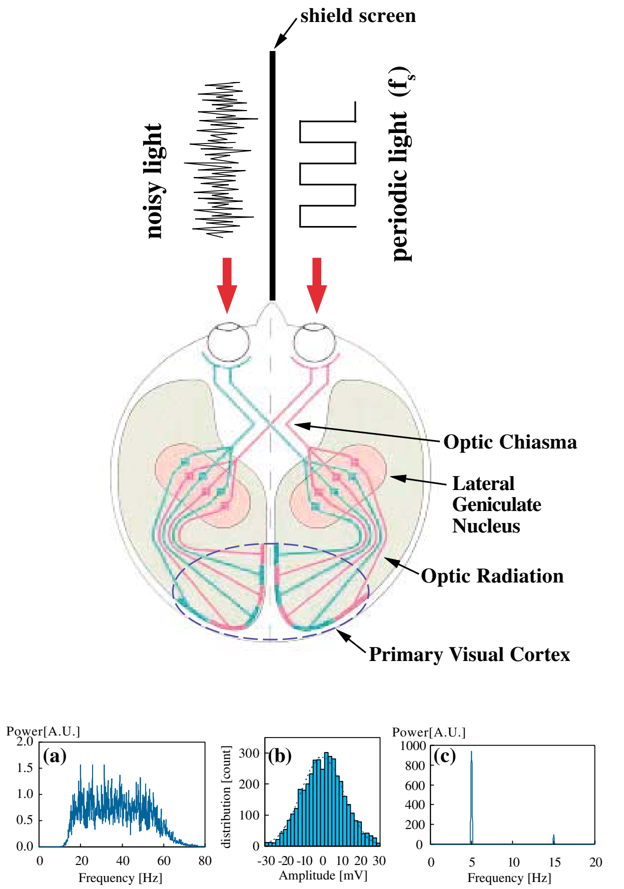

FIG. 1 (color). The experimental protocol and the trajectory of the photic stimulus from the eyes to the primary visual cortex. Visual stimuli from right and left eyes are projected via the optic chiasma onto corresponding hypercolumns (not shown) at the primary visual cortex with a distribution between brain hemispheres that is species dependent. In the human brain, the visual stimulus is equally divided between the left and right hemispheres; i.e., 50% is projected onto the right and 50% onto the left hemisphere of the brain. Characteristics of the photic stimuli. (a) Power spectrum of the noisy stimulus; (b) amplitude distribution of the noisy stimulus, the dotted line indicates a Gaussian distribution; and (c) power spectrum of the periodic stimulus.

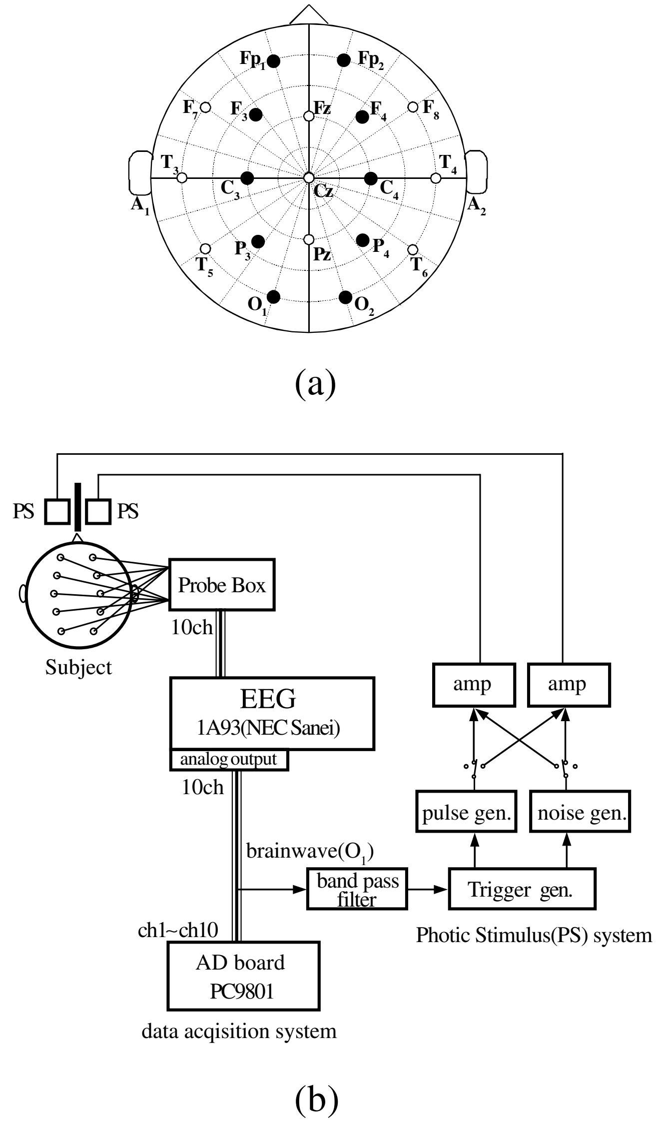

FIG. 2. International 10–20 electrodes arrangement (a) and experimental setup (b) for measurement of brain waves. Following the 10–20 international electrode system, target electrodes in this study were positioned at ten fixed points on the scalp using the linked-earlobe references.

Then we calculated the power spectrum density of the brain waves. The details of the data analysis and experimental setup have been already described elsewhere [14,24,25].

We can study SR phenomena in the central nervous systems by applying the noisy signal only to the left eye and the periodic one only to the right eye. This is because, with this protocol, the signals are mixed in the visual cortex after the optic chiasma as shown in Fig. 1. Furthermore, it avoids stimulating SR in the eyes or retina which, similar to many primary sensory organs [3–5,8,10], may also exhibit SR when the signals are mixed before application to the eyes. In addition, we avoid cross talk of photic stimuli by inserting a lightproof screen between the right and the left eyes (see Fig. 1).

First, only a periodic stimulus was applied to determine the threshold stimulus for entrainment of brain waves in the α-frequency range. Figure 3 shows a normalized power spectrum density, $P_e^N = P_e/P_0$, where P_0 is the total power intensity in the spectrum for each stimulus and P_e, the power intensity of the brain wave entrained at the stimulus frequency. The stronger the light intensity, the larger the normalized spectrum density, P_e^N. That is, more α oscillators are synchronized with stronger light intensity at the stimulus frequency.

There are two types of entrainment depending on the subject: one at a stimulus frequency f_s (we call it just "entrainment" or "fundamental entrainment") and a second one at a harmonic frequency of f_s [23]. Fundamental entrainment for $f_s \sim f_\alpha$ is usually most predominant but often influenced by the subject's mental and physical condition (e.g., stress) at the moment of testing, while harmonic entrainment is rather insensitive to such

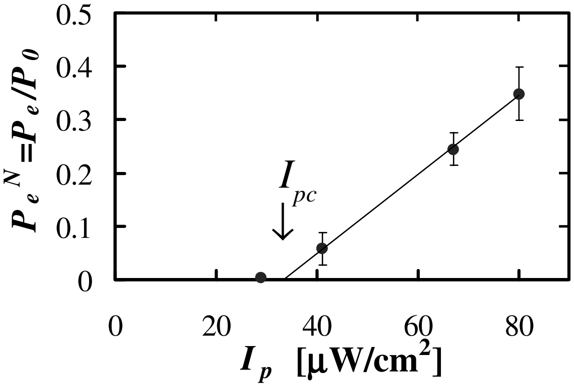

FIG. 3. Stimulus intensity I_p vs the normalized power density $P_e^N = P_e/P_0$, where P_0 is the total spectrum power, at O_1 (subject: S). Here, $I_{pc} = 33.4\ \mu\mathrm{W/cm^2}$.

uncontrollable factors [23]. The entrainment threshold for stimulus frequency, f_s ($f_s \sim f_\alpha$), is determined to be $I_{pc} = 33.4\ \mu\mathrm{W/cm^2}$. It was confirmed that there was no entrainment at $I_p = 30\ \mu\mathrm{W/cm^2}$, i.e., $I_p < I_{pc}$.

We checked that the intensity of the periodic stimulus, I_p, for the SR experiment was below threshold, I_{pc}, for all subjects. That is, no peaks were observed in the spectrum, neither at the fundamental nor at the harmonic frequency for all subjects, because of subthreshold. We note, in general, that the greater the absolute difference between the stimulus frequency, f_s, and f_α, the higher the intensity threshold for entrainment. Thus, in particular, the threshold at $f_s = 1/2 f_\alpha$ is always higher than that for fundamental entrainment, i.e., when $f_s = f_\alpha$.

For the SR experiment, with the application of a periodic light stimulus at fixed frequency 5 Hz and fixed amplitude $I_p = 30\ \mu\mathrm{W/cm^2}$, the light intensity, I_n, of the noisy light stimulus was varied. Figure 4 shows the brain wave spectra for various I_n on the electrode position O_1. When $I_n = 0$, there is no entrainment peak, P_e, neither at the fundamental, 5 Hz, nor at the harmonic, 10 Hz.

As the noise intensity, I_n, is increased, a clear entrainment peak is observed in the spectrum at $f = 10$ Hz. In Fig. 4e, P_e is maximum at $I_n^* = 54.5\ \mu\mathrm{W/cm^2}$. When the noise intensity is further increased, P_e decreases. That is, there is an optimum noise intensity for entrainment with the bell-shaped dependence on noise intensity that is the signature of SR.

While a typical example has been shown in Fig. 4 for the subject S, Fig. 5 shows that the effect is universal, i.e., independent of subjects. Here a normalized P_e is plotted against a normalized I_n for all five subjects. As the maximum power spectrum density, P_e^*, and the optimum noise intensity, I_n^*, depend on subjects, the normalized spectrum density, $P_N = P_e/P_e^*$ and noise intensity $Q_N = I_n/I_n^*$ are used to show the bell-shaped noise dependence of SR for all subjects. That is, the optimum intensity of the noisy stimulus synchronizes more α oscillators in the human brain. We retested several of these subjects on subsequent days and obtained similar results.

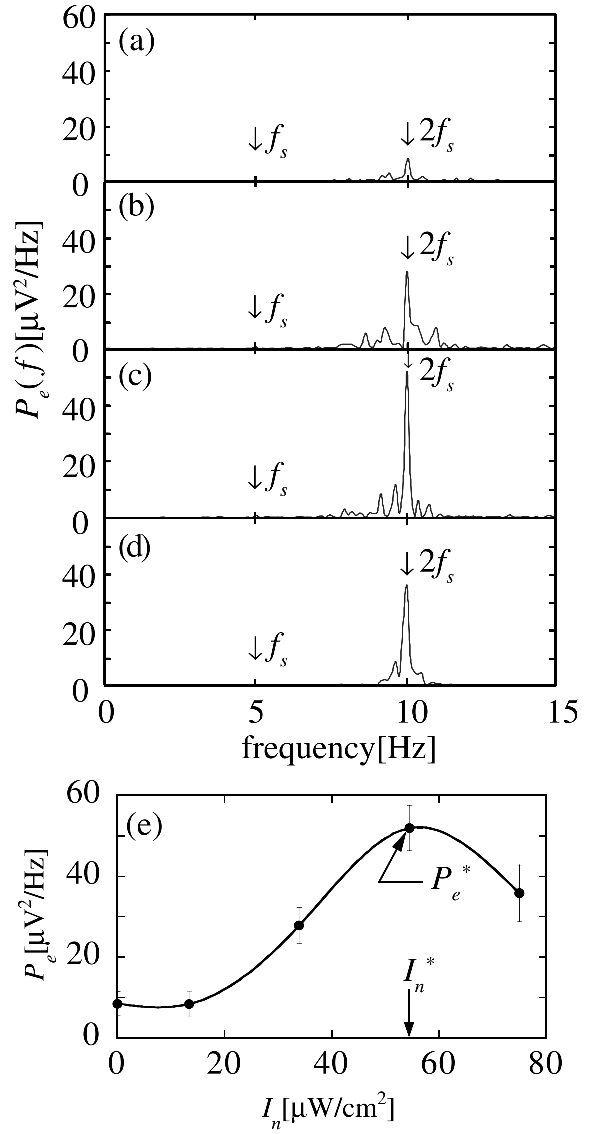

FIG. 4. Power spectrum of the brain wave at O_1, i.e., the left occipital (subject: S). (a) $I_n = 13\ \mu\mathrm{W/cm^2}$, (b) $34\ \mu\mathrm{W/cm^2}$, (c) $54\ \mu\mathrm{W/cm^2}$, (d) $75\ \mu\mathrm{W/cm^2}$. A sharp peak in the power spectrum is observed at the harmonic frequency $2f_s = 10$ Hz of the stimulus ($f_s = 5$ Hz) in (a) to (d). Here f_s is close to $1/2 f_\alpha$, that is, the subharmonic frequency of the α wave. (e) The entrainment power density, P_e, shows the bell-shaped dependence as a function of the noise intensity I_n. Here $P_e^* = 51.9\ \mu\mathrm{V^2/Hz}$ and $I_n^* = 54.5\ \mu\mathrm{W/cm^2}$.

We have presented here the first observation of SR in an information processing area of the central nervous system. By studying noise induced entrainment in the α wave, we found evidence of SR which is universal independent of subjects. Here we do not observe SR at input organs such as eyes and retinas because, for each subject, both noisy and subthreshold periodic photic stimuli are independently applied, respectively, to the left and right eyes. In this protocol, as shown in Fig. 1, since both left fields of view are wired to the right cerebral hemisphere and both right fields of view are wired to the left cerebral hemisphere, the signal and noise are mixed not in the eyes but in the

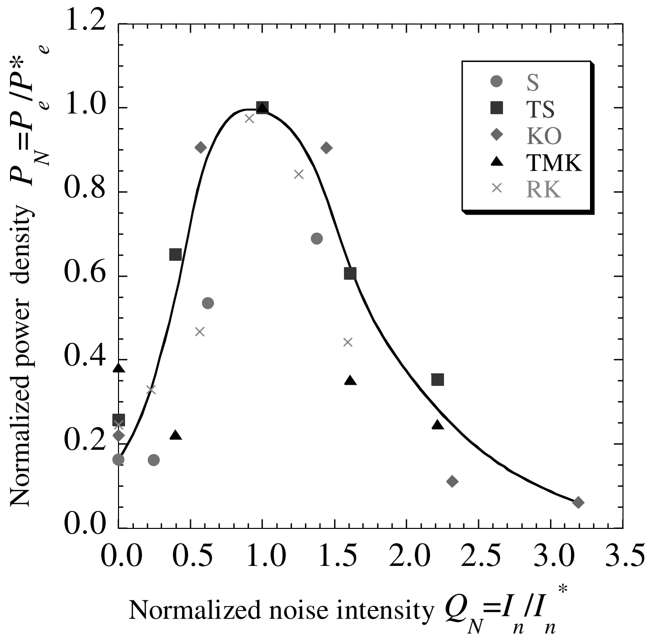

FIG. 5. Universality of stochastic resonance in the alpha wave at O_1 (all subjects) shown by the normalized power density at the eye: $P_N = P_e/P_e^*$ vs the normalized noise intensity, $Q_N = I_n/I_n^*$ (five subjects: S, TS, KO, TMK, and RK).

visual processing areas of the brain. Thus, we bypass sensory organs and observe the SR in the visual cortex itself. There have been many previous reports of SR in sensory organs and some reports of SR in brain tissue *in vitro*. However, no one has exploited the present protocol. The SR reported in Fig. 5, observed in multiple subjects multiple times, must occur in the visual cortex. Since there are many possible internal electrochemical noise sources in the brain, this suggests that higher brain functions, such as perception and cognition, may exploit SR.

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