Applying stochastic resonance to magnify $\mu$ and $\beta$ wave suppression

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Abstract

The goal was to test whether band-limited sensory noises with adequate amplitudes, by the principle of stochastic resonance, could enhance $\mu$ and $\beta$ wave suppressions. Scalp EEG was recorded while the subject performed thumb movements in the presence of vibratory noises applied to the thenar belly or thumb tip. Seven subjects without clear $\mu$ or $\beta$ wave suppression in the absence of the mechanical stimuli were recruited. The results showed that when the stimuli were applied to the thenar belly, both $\mu$ and $\beta$ wave suppressions were enhanced in a bell-shaped trend (the characteristics of stochastic resonance) in four subjects.

Keywords: Stochastic resonance; $\mu$ wave suppression; $\beta$ wave suppression

1. Introduction

Electrical activities (electroencephalogram, EEG), which reflect the state of brain activations, can be non-invasively recorded on the scalp. $\mu$ rhythm is the 8–12 Hz waveform recorded at the Rolandic area of cortex (C3 and C4 of the standard international 10–20 electrode system) while the subject is wakeful and relaxed. Since $\mu$ rhythm is suppressed by the voluntary movements and sensory stimuli of contralateral upper limbs [1], it is a potential candidate for the control source in brain–computer interface (BCI) technology [2–5]. The main problem in using $\mu$ wave for detecting movement attempts has been the great variability of success rates among subjects. The success rates of many subjects remained low even after extensive signal processing [6–9].

Benzi first noted that, in contrast to the instinctive judgment, a superimposed noise could enhance the detection of desired signals [10,11]. The intensity of noise is very critical. There is an optimal intensity near the detection threshold. When the intensity of noise is either too small or too large, the detection rate is reduced. In other words, the magnitude of response as a function of the noise intensity is bell-shaped. Some investigators took advantage of stochastic resonance to improve the tactile sensation in older adults by electrical noise stimulation [12]. Though stochastic resonance has also been verified in many different biological systems [13], reports of this effect in EEG are only handful. One recent study [14] that investigated stimulating one eye with a subthreshold periodic optical signal and, simultaneously, the other eye with noise light and recording EEG response of the occipital region demonstrated that the phenomenon of stochastic resonance was valid for EEG. The frequency of input periodic signal was 5 Hz and the power spectrum of EEG at 10 Hz was analyzed. In another study [15], authors showed stochastic resonance of EEG in somatosensory area elicited by mechanical tactile stimuli to the middle finger. The EEG content of the same frequency band (2.5 Hz) as the input signal (periodic mechanical stimuli) was analyzed. The effects of noise on the other frequency bands of EEG were not mentioned. If the phenomenon of stochastic resonance is also valid for $\mu$ wave suppression during the thumb movements, then it may be possible to design devices accordingly to improve the detection rate of movement attempts. Since the input noise is a sensory stimulation and the output measure is related to motor attempts, the whole system tested involves the sensory pathway, the motor attempt generator and the integration center of motor-sensory information. The whole

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system is very complex. As far as the authors know, there is no existing study report to answer this question.

The main purpose of this study was to investigate the existence of stochastic resonance in \( \mu \) wave suppression where the noise input was the tactile stimulation. The working hypothesis was that the stochastic resonance also existed in \( \mu \) wave suppression during thumb movement and that superimposing a band-limited random tactile stimulation with a proper intensity could produce larger \( \mu \) wave suppression during the movements.

2. Methods

2.1. Experimental setup (Fig. 1a)

The experimental setup consists of two subsystems, namely, the bio-signal acquisition system and the stochastic tactile stimulator system. The bio-signal acquisition part was responsible for recording EEG and EMG (electromyography) and the stochastic tactile stimulator provided mechanical stimulus to the hand.

EEG was recorded by using a commercial digital EEG recorder (Profile, Medelec, Oxford Instrument, http://www.oxford-instruments.com) and all experiments were performed in a shielded room. Eleven channels of signals, including 10 channels of scalp EEG and one channel of surface EMG from the right thumb extensor, were recorded, respectively (Fig. 1b). All EEG electrodes were referenced to the left earlobe (A1). The four electrodes, each 2 cm from C3 and forming a cross (Fig. 1c), were used for spatial filtering at the software level. The four electrodes surrounding C4 were used similarly. EMG of thumb extensor was used to define the onset time of thumb movements. EEG signals were filtered by a 0.5–100 Hz analog bandpass filter, amplified by 10000\( \times \) and sampled at a rate of 256 Hz per channel. EMG was also amplified, filtered and sampled at an identical rate by the same EEG machine.

2.2. Mechanical stimulator

The main function of the stochastic tactile stimulator was to produce pointed mechanical stimuli (pointed blunt stabs) on skin with adjustable intensity and frequencies. More specifically, (1) the size of the stimulator had to be small enough so that the device could be fixed on the thumb and would not interfere with the thumb movements and (2) the frequency response had to be linear in the 0–50 Hz range, so that the device could be easily driven to produce band-limited random mechanical stimuli with specified intensities.

Fig. 2 shows the size and structure of our custom-made mechanical stimulator. In order to characterize the dynamics of the stimulator, we used pseudo random binary sequence as the command to drive the stimulator and a proximeter to record its response (Fig. 3a). It was clear that the response is fairly linear when the frequency was below 1000 Hz. An empirical model of the stimulator as a second-order system (Fig. 3b) was identified by least squares method

\[
-0.1601s^2 - 1290s - 5.363 \times 10^6 \\
+ 538.3s + 1.172 \times 10^7 
\]  

(1)

In repeated tests within 50 Hz, the model simulation results matched with the real responses faithfully.

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2.3. Experimental procedures

The study protocol was approved by the human experiment and ethics committee of the local medical center. Before the experiment, the whole experimental procedure and the potential hazards were explained clearly to the subject and a written document was signed. The subject sat on a chair with the right upper limb well supported. The forearm was in neutral position with the fingers in naturally flexed posture. Electrodes were fixed on the scalp and the right forearm by the standard clinical procedure. Before the trials, the subject was asked to be calm and relaxed for 20 min. The duration of one trial was 30 s and within which there were two movements separated by approximately 10 s. When the subject heard the auditory cue produced by the experimenter, he was asked to make a fast and brief thumb extension and natural falling back to the original position. The tactile stimulator was attached on the midpoint of right thenar muscle and was turned on throughout the whole trial of 30 s. Since the sensory threshold of mechanical stimulation was about 0.02 mm, we chose 0.01, 0.02, 0.04, 0.06, 0.08 and 0.1 mm for stimulation in this study. The intensity of mechanical stimulation was changed in a random fashion for different trials, though the total number of trials using each amplitude was identical. The number of total trials for one
amplitude was 20. The tactile stimulation was switched to the palmer side of the thumb tip and the experiment was repeated. There was sufficient time for rest between consecutive trials in order to prevent interaction among trials.

Before this study, we did a preliminary test to observe the response magnitude of $\mu$ wave suppression. We deliberately chose subjects that did not show clear $\mu$ wave suppression during thumb movements without tactile stimulation (Fig. 4). Seven young male subjects were recruited. The subjects were healthy and had no known neurological deficits.

### 2.4. Data processing

EMG envelope was computed by the following procedures: (1) high-pass filtering by a fourth-order Butterworth filter with a cutoff frequency at 64 Hz, (2) taking the absolute values and (3) low-pass filtering by a fourth-order Butterworth filter with a cutoff frequency at 3 Hz. The movement onsets were defined by the peaks of the calculated EMG envelope.

EEG recordings of the four electrodes surrounding the C3 electrode were used to perform the Laplacian operation as a spatial filtering:

$$E'_{C3} = E_{C3} - \frac{(E_1 + E_2 + E_3 + E_4)}{4}$$ (2)

where $E'_{C3}$ was the filtered EEG at C3, $E_{C3}$ was the original EEG at C3, and $E_1$, $E_2$, $E_3$ and $E_4$ were the EEG of the four electrodes surrounding the C3 electrode. The five channels of EEG from the right hemisphere were processed similarly to derive $E'_{C4}$, the filtered EEG at C4. $E'_{C3}$ and $E'_{C4}$ are bandpass (4–40Hz) filtered by a fourth-order Butterworth filter.

After preprocessing, EEG data were then aligned by the peaks of EMG, representing the start of movement ($T_m$), and cut into segments of 12 s with $T_m$ at the center of the segment. The segments were passed through a windowed FFT with a Hamming window of 1 s width and shifted per 0.5 s. The absolute values of Fourier coefficients of 10–12 Hz were summed as the amplitude of $\mu$ rhythm. ERD were defined as (Pfurtscheller et al., 1998)

$$\text{ERD} = \frac{(\mu \text{ amplitude} - \text{mean } \mu \text{ amplitude})}{\text{mean } \mu \text{ amplitude}} \times 100\%$$ (3)

where mean $\mu$ amplitude was the $\mu$ amplitude per second over the first 1 s. ERD of $\beta$ rhythm (15–25 Hz) was calculated similarly.

### 2.5. Statistical analysis

We used suppressive value (SV), which was defined as the ERD difference between the first point and the first local minimum in the time interval of $-2$ to $+2$ s, for statistical inference. The difference of SV between results with and without stimulation was tested with paired $t$-test at the confidence level, $\alpha = 0.9$.

### 3. Results

The results of mechanical stimulation in one subject were shown in Fig. 5. When the intensity of tactile stimulation was 0.01 mm, there was no clear $\mu$ wave suppression. Suppression appeared when the stimulation amplitude was 0.02 mm. The degree of suppression reached a maximum when the intensity of stimulation was 0.04 mm and decreased as the intensity increased more. Fig. 6 summarized the results of $\mu$ and $\beta$ wave suppression at C3 electrode in all subjects when the tactile stimulation was applied to the thenar belly. Two figures showed
Fig. 5. The results of an example subject. ERD was augmented by tactile stimulation with appropriate intensity (0.02, 0.04 and 0.06 mm). The number at left lower corner is the intensity of mechanical stimulation. Bars stand for 95% confidence interval.

Fig. 6. Summary of results when the mechanical stimulation was applied to the thenar belly. Upper and lower plots showed the averaged results of $\mu$ and $\beta$ wave suppression at C3 electrode, respectively. The lengths above the plot represent the amplitudes of mechanical stimulation. Bars stand for 1 standard deviation and asterisks stand for significant difference from results of no stimulation.

A very similar trend. Tactile stimulation had significant effects on $\mu$ and $\beta$ wave suppression during thumb movements in four (S1, S3, S5 and S7) subjects. In these four subjects, the magnitude of suppression presented a bell-shaped (crescendo–decrescendo) tendency. In other words, there was a stimulation intensity that could produce the largest suppression. In addition, $\mu$ wave in one subject (S2) also showed similar bell-shaped tendency, though the effect did not have any statistical significance.

Fig. 7 summarized the results of $\mu$ and $\beta$ wave suppression at C3 electrode when the tactile stimulation was applied to the thumb tip. There was no bell-shaped tendency in any subject as was seen during thenar belly stimulation. For $\mu$ wave, the amplitude of suppression was largest when the stimulation intensity was the smallest (0.01 mm) in six subjects. The difference had statistical significance in two subjects. For $\beta$ wave, the amplitude of suppression was largest when the stimulation intensity was the smallest (0.01 mm) in three subjects. The difference had statistical significance in two subjects.

The results at C4 electrode were in general independent of stimulation amplitude, i.e., only one subject showed
bell-shaped phenomenon and none reached statistical significance. This trend also supports that the EEG results were not caused by artifacts of direct mechanical vibration. The reason is that, if the rhythms in the EEG were caused by direct motion artifacts, electrodes at the right hemisphere should have a higher amplitude that increased with increased stimulation amplitude.

Fig. 8 presented the relationship between the normalized SV (using the maximum SV as the base) and the normalized stimulation intensity (using the stimulation intensity that produced the maximum SV as the base) in the four subjects that demonstrated significant effects of mechanical stimulation. These curves better demonstrated the bell-shaped tendency, which was characteristic for stochastic resonance.
4. Discussion

$\mu$ wave suppression is a highly complex and non-linear phenomenon, involving transmission of sensory information of hand to the sensory cortex, movement attempt formation in premotor cortex and interaction of sensory information and motor attempt in motor cortex to generate motor commands. There is no existing data about the adequate frequency range of noise for sensory information to induce the phenomenon of stochastic resonance. We empirically chose 0–50 Hz as the frequency band of the noise under the following reasons: (1) it was within the functional range of skin receptors of mechanical stimuli and (2) it produced stimulation on both Meissner and Paccinian corpuscles [16]. For the intensity of the noise, we used values just above the threshold.

As described in the Results section, the relationship between SV and stimulation magnitude was different for stimulating thenar belly and thumb tip. The difference might be explained by the difference in the sensory threshold of the two locations. It is well known that the sensory threshold for the pure sinusoidal stimulation is smaller at the thumb tip. We tested four of our subjects with the band-limited noise stimulation. The preliminary results (Table 1) also supported the same assertion. All subjects could feel the stimulation at the thumb tip when the amplitude was as small as 3 $\mu$m, while they failed in more than 50% of tests when the simulation was at the thenar belly. The stimulation intensity used in this study was close to the skin sensory threshold at thenar belly and the response showed the characteristic of stochastic resonance, i.e., a bell-shaped relationship between noise intensity and response magnitude. On the other hand, the stimulation intensity might not be small and close enough to the threshold at the thumb tip, so that the enhancement of response was only observed for the smallest stimulation intensity. In other words, the optimum noise intensity might be smaller than the smallest intensity that we chose. The other possible factor was that stimulating thenar belly, due to its proximity, was more likely to excite proprioceptors that were more related to $\mu$ suppression.

In this study, we observed that tactile stimulation enhanced $\beta$ wave peri-movement suppression but not post-movement rebound augmentation. The response was peculiar in the sense that, instead of peri-movement suppression, post-movement rebound augmentation was usually more prominent for $\beta$ wave [17]. In this study, we deliberately chose those subjects without clear $\mu$ and $\beta$ responses to thumb movements in the absence of tactile stimulation. It needs further study to test whether the tactile stimulation has a differential influence on $\mu$ and $\beta$ waves or the peculiarity is solely due to the selection of a special subject group.

In this study, we demonstrated that band-limited white-noise mechanical stimulation enhanced the $\mu$ wave suppression in some subjects who showed no clear suppression in the absence of tactile stimulation. The phenomenon can potentially be used to increase the numbers of subjects that can benefit from using BCI systems based on detecting $\mu$ wave suppression. The stimulator can be incorporated into the prosthesis and active orthoses to be controlled by the BCI system. Currently, we are developing such active hand orthoses. In addition, since $\mu$ wave suppression was enhanced, it is likely that the devices and the principle can be used to preserve or increase the functional territory of sensory cortex in stroke patients.

5. Summary

Objective: To test whether band-limited sensory noises with adequate amplitudes, by the principle of stochastic resonance, could enhance $\mu$ and $\beta$ wave suppressions.

Methods: Scalp EEG was recorded while the subject performed thumb movements in the presence of vibratory noises to the thumb tip or thenar belly. The sensory noises were pointed stabbings produced by a small mechanical vibrator driven by band-limited (0–50 Hz) white noise commands. The intensity of the mechanical stimuli was systematically changed and the magnitudes of $\mu$ and $\beta$ wave suppression were analyzed. For each stimulus intensity, 40 thumb movements were performed and the results were averaged. Seven subjects without clear $\mu$ or $\beta$ wave suppression in the absence of the mechanical stimuli were recruited.

Results: When the stimuli were applied to the thenar belly, both $\mu$ and $\beta$ wave suppressions were enhanced in a bell-shaped trend (the characteristics of stochastic resonance) in four subjects. On the contrary, when the stimuli were applied to the thumb tip, both $\mu$ and $\beta$ wave suppressions were enhanced when the amplitude of stimuli was the smallest one.

Conclusion: Band-limited white noise mechanical stimuli with adequate intensity could enhance $\mu$ and $\beta$ wave suppressions in some subjects that originally showed no clear suppression.

Conflict of interest statement

The authors declare that there is no conflict of interest with other researchers, research groups or companies.

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References


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