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A Portable Wireless EEG System for Neurofeedback: Design and Implementation

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Abstract

Human can learn how to shape their brain electrical activity in a desired direction through continuous feedback of the electroencephalogram (EEG), and this technique is known as Neurofeedback (or EEG biofeedback), which has been used since the late 1960s in clinical applications. In this study, a portable wireless EEG (named wEEG) has been designed and implemented, which consists of a mobile station (a wireless two-channel EEG acquisition device) and a base station (a bridge between mobile station and computer). Moreover, a SensoriMotor Rhythm (SMR) training system was also implemented with the wEEG for enhancing attention with virtual environment. Experiment results based on 16 volunteers' (8 females and 8 males, average age is 27±4) were reported in this paper. The results show that the SMR ratio of 87.5% subjects increased about 0.7% in training status than that in the stable status. With the proposed system, many training protocol scan be designed easily and can be done at home in our daily life conveniently. Additionally, the proposed system will be useful for disabled and aged people.

Key words : electroencephalogram, neurofeedback, attention enhancement training

I. INTRODUCTION

The EEG is a particularly powerful clinical tool and has been taken as the gold standard for neurology and psychology research for decades. It is a relatively simple, inexpensive and completely harmless method for analyzing the brain activity. Based on different frequency bands, EEG signals can be categorized into 4 specific categories of brain activity, which have been commonly discussed in EEG literature: Delta, Theta, Alpha and Beta waves as shown in Table 1.

Neurofeedback is a technique used mainly in behavioral medicine as an adjunct to psychotherapy. An electronic device records EEG activities at a particular scalp location, extrapolates physiological measurements from the signals and then converts them to visual and/or auditory representations, which dynamically cover with the brain signals. The aim of this study is to develop a portable biofeedback system for enhancing the human ability to self-regulate brain electric activity. With the proposed system, some computer assisted neurofeedback training can be done at home conveniently in our daily life.

Neurofeedback is a learning strategy. It enables persons to alter their brain waves, when information of a person's own brain wave characteristics is made available to him or her, he or she can learn to change them. Neurofeedback likes a mirror to us, telling us how we look at a given instant in terms of how well our brains being working. We can think of it as "exercise" for our brain. The most common application of Neurofeedback is currently to the Attention Deficit Hyperactivity Disorder (ADHD), sleep problems in children, teeth grinding, and chronic pain, etc. The training is a painless, non-invasive procedure, and it is also helpful with the control of mood disorders, such as anxiety, depression, medically uncontrolled seizures, minor traumatic brain injury or cerebral palsy.

During these years, many studies of Neurofeedback treatment have reported promising results for ADHD, depression, and epilepsy. Many Neurofeedback training systems have been designed and developed. Zhang Zuoseng et al have developed an Alpha frequency band EEG biofeedback system in 1988 [1]. They designed an EEG acquisition device by themselves for biofeedback system. Their experiment results showed the feasibility of using EEG biofeedback training to enhance a person's alpha component. Jennifer et al have developed an EEG biofeedback system using virtual environments for training a subject to maintain his or her EEG

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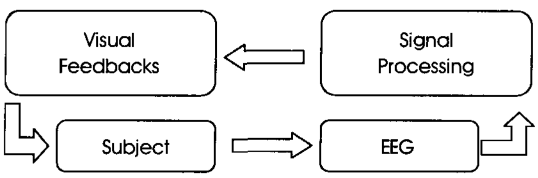


Fig. 1. Framework of Neurofeedback system.

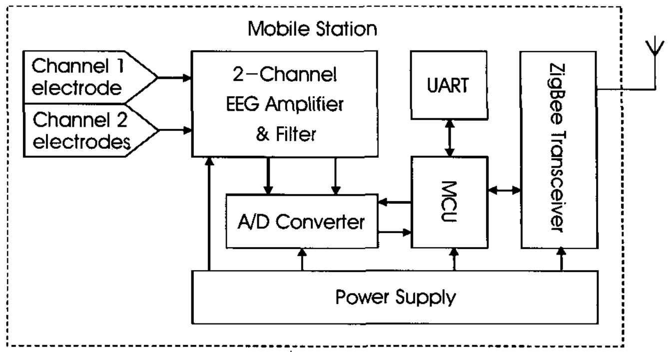


Fig. 2. Block diagram of wEEG Mobile Station.

component signal amplitude for a predetermined period in 1999 [2]. Othmer et al proposed the use of EEG biofeedback with virtual reality in 2000 [3]. V. A. Grin et al reported the effect of Neurofeedback training for enhancement of attention which showed that the ratio between trained sensorimotor rhythm power and the power of the rest EEG spectrum increased by 30-100% during the 4 minutes of training in 2001 [4]. In 2002, an attention enhancement system using EEG biofeedback in virtual environment has been reported by B.H. Cho et al [5]. They proposed a virtual reality method for treating ADHD children and increasing the attention span of children who have attention difficulty. Their experiment results showed their system can possess the ability to improve the attention span of ADHD children and it's useful to help them to learn to focus on some tasks. And, Marco Congedo et al proposed a low-resolution electromagnetic tomography neurofeedback to enhance the human ability to self-regulate brain electric activity in 2004 [6]. Moreover, Andrija et al introduced a music therapy and computer game-based EEG biofeedback training system to help students de-stress for improving academic performance in 2005 [7], and Vincent J. Monastra et al gave a review of EEG biofeedback in the treatment of ADHD [8].

Fig.1 shows a commonly used framework of Neurofeedback system. The EEG signals are measured from the pre-specified position of subject's scalp. After the signals being processed, the analysis results are displayed visually through screen to subject. Finally, the subject can do some efforts to adjust his or her mental status from the visual feedback to get more efficient expected results. Therefore, some mental disorder disease (e.g. ADHD) can be treated using such Neurofeedback training.

As mentioned above, the virtual reality technology has been employed in the area of EEG biofeedback recently [2, 3, 5]. There is no doubt that virtual environment can get the subjects' attention more easily and make them increase their ability to concentrate on object, since it owns three "I's characters: Immersion, Interaction, and Imagination [9]. In our system prototype application, we also designed a biofeedback training program with virtual environment, and the collected EEG from a subject's scalp will be translated into movement and interaction within the program.

Unfortunately, among these developed systems, most of them are constructed by employing a commercial EEG device. It will make the desired system huger and more costive as some useless functions for the specified system might be included in commercial devices, and it is difficult to make a more flexible and efficient biofeedback system with a commercial one. Therefore, it is necessary to develop a tiny single or double channel EEG acquisition device for biofeedback. Nowadays, advances in integrated circuits and wireless communications have enabled the design of low-cost, miniature, lightweight, and low power devices. With such a wireless EEG acquisition device, EEG signals can be

Table 1. Overview of specific brainwave types and their associated state of consciousness.

Brainwave Frequency	State of Consciousness
Beta (13–30Hz)	Fully–Awake, Alert, Excitement, Tension
Alpha (8–12Hz)	Deeply–Relaxed, Passive–Awareness, Composed
Theta (4–7Hz)	Drowsiness, Unconscious, Deep–Tranquility, Optimal Meditative State
Delta (below 4Hz)	Sleep, Unaware, Deep–Unconsciousness

measured more conveniently. Low power transceiver is essential to a portable wireless device, so we selected the popular low power wireless solution in our proposed device. It is more acceptable in comparison with a common one for users, especially for aged people, children, and disabled.

In this paper, a tiny two-channel wireless system named "wEEG" based on Radio Frequency (RF) technology was designed and developed as the EEG acquisition device. The structure of wEEG will be described in detail in the next section. Furthermore, we also implemented a system prototype application to build a virtual environment for attention enhancement training, which takes the low fast Beta wave (12-15Hz, formerly SMR) and Theta wave (4-8Hz) into account as the biofeedback training frequency parameter, and our experiments aim at studying the ability of a person to enhance his or her attention for a given task.

II. DESIGN OF THE SYSTEM

The proposed system consists of two main parts: EEG acquisition sub-system (wEEG) and computer assisted training program. The wEEG includes a mobile station and a fixed station. The mobile station is the wireless EEG conditioning unit, and the fixed station acts as a bridge between mobile station and host PC. The training protocol is defined in the computer assisted program. These will be introduced in the follows subsections.

A. wEEG' Mobile Station

The mobile station makes the Neurofeedback system more flexible and efficient, since it is a wireless, portable two-channel tiny EEG acquisition device. The total gain is about 80dB, and the default programmable sample rate is 256Hz and resolution of 12-bit for two-channel EEG signals. Fig.2 shows the block diagram of the mobile station, which consists of two-channel EEG conditioning part, microprocessor, Zigbee transceiver and power supply. The main parts of it are listed and described as follows:

a) EEG amplifier and filter: As has been stated earlier, because EEG signals typically have an amplitude in range of 10~100uV, amplification prior is requiring to any signal processing. The skin typically provides source impedance on the order of 1-5Mohm. To better acquire the signal, the amplifier must match the source impedance or have greater input impedance than the source impedance. Furthermore, the amplifier must reject 60Hz (or 50Hz) power line interference from the signal. Consequently, a relatively high common mode rejection ratio (CMRR) is desired. Under these conditions, a high input impedance, high CMRR and moderately high gain instrumentation amplifier is selected as the preamplifier component of the EEG amplifier. The chip selected is INA128 from Texas Instruments [10], which is a real low power, general purpose instrumentation amplifier due to the fact it requires low input bias current. It also features a high CMRR of 120dB and a differential input impedance of 10Gohm || 2pF.

In order to get the whole efficient EEG band (0.15Hz-100Hz), we have to use amplifiers and filters to do EEG conditioning. From the instrumentation amplifier, a 4th-order Bessel LPF (Low Pass Filter) attenuates frequencies up 100Hz. The signal is then filtered by a 2nd-order Butterworth HPF (High Pass Filter) to attenuate frequencies below 0.15Hz. After band-pass filtering, the signal goes to an operation amplifier as the main amplifier which to amplify the filtered signal by 40dB. After that, the signal goes to a 60Hz notch filter to reject the 60Hz interference. Finally, the signal is gained by a 2nd amplifier with 12dB. The operation amplifier chip used here is LMC6464 from National Semiconductor [11], which is a low power operation amplifier with Rail-

Table 2. Specifications of wEEG's amplifier & filter.

Part name	Character	Gain
Pre-amplifier	Differential input impendence: 10Gohm||2pf, CMRR: 120dB, input bias current: 1nA input offset voltage: 25uV	25dB
Low pass filter	4th-order Bessel filter cutoff frequency: 100Hz	0dB
High pass filter	2nd-order Butterworth filter cutoff frequency: 0.15Hz	0dB
Main amplifier	Invert amplifier	40dB
Notch filter	60Hz Twin-T notch filter	0dB
2nd amplifier	Invert amplifier	12dB

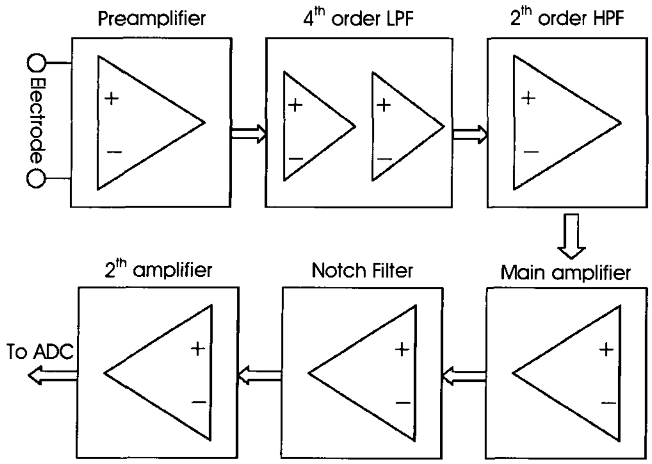


Fig. 3. The structure of amplifier and filter.

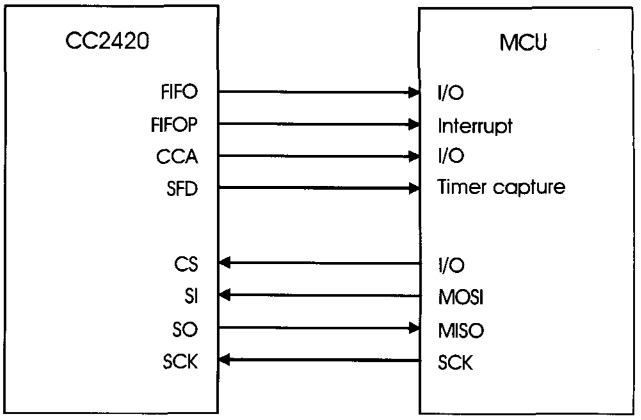


Fig. 4. Microprocessor interface of CC2420.

to-Rail input and output. The structure of this part is shown in Fig.3. The specifications of wEEG's amplifier and filter part are given in Table 2.

b) ZigBee transceiver: This is the most important part in the mobile station. It transmits the digital EEG signal wirelessly. The ZigBee transceiver used in this system is the CC2420 from Texas Instruments [12], which is a low power, narrow band, 2.4GHz ISM band RF chip, and it can provide a data rate up to 250Kbaud.

The microprocessor interface is shown in Fig. 4. CC2420 can be configured, such as changing mode, reading and writing buffered data, and reading back status information, via the 4-wire SPI bus configuration interface (SI, SO, SCLK and CS). FIFO and FIFOP status pins can be used to interface to the receiving and transmitting FIFOs, the CCA pin is for clear channel assessment, and the SFD pin can be used for timing information. We did not use SFD pin in the current application as it is particularly for beaconing networks.

c) Microprocessor: An inexpensive 8-bit 8051-based microcontroller and a 12-bit resolution A/D converter (ADC) are employed in this design to acquire EEG signal and drive RF transceiver. The voltage range of the ADC is from -2.047V to +2.048V and it can cover the amplified EEG signal to convert it to digital one. To drive the ZigBee transceiver, about 4 general I/O pins, 1 external interrupt pin and SPI bus are necessary for configuration and signal as shown in Fig. 4.

d) Power supply: We are now using a 9V battery to supply it temporarily, and we are considering a small size Li-Ion rechargeable instead.

Additionally, the PCB (Printable Circuit Board) artwork for the designed wEEG is on-going, and the expected size of two-channel mobile station is about 50mm×50mm×20mm without battery.

B. Base Station of wEEG

The proposed base station acts as a bridge between the mobile station and host PC transferring the received EEG signals to host PC. Fig. 5 shows the block diagram of wEEG's Base Station.

C. SMR Training Procedure

As mentioned above, low Beta brainwaves (SMR) can be used to reflect ADHD in clinic as lack of focused attention with lower SMR power ratio. Therefore, for attention enhancement, SMR training is helpful to produce relaxed focus and improve attentive abilities with increasing SMR. In this study, the SMR band power is selected as a training parameter to generate visual feedback.

Since EEG signals are non-stationary, the SMR band power will be different from each individual. So, the stable state SMR power ratio has to be calculated as the threshold value ($SMR_{threshold}$)before training for latter using, and the SMR power ratio is defined as Eq. (1).

$$SMR(t)\% = \frac{\sum_{f \in SMR} P_n(f)}{\sum_{f=4}^{30} P_n(f)} \times 100\% \tag{1}$$

Where $P_n(f)$ is the power spectral density between times $t-1$ and t. SMR(t) is thus the instantaneous ratio of the integral of power in the SMR (12-15Hz) and all pass frequency band (4-30Hz). Fig.6 shows the procedure for estimating the SMR power ratio.

In our current prototype training program, a car racing game was developed to induce SMR band activity, so, the output

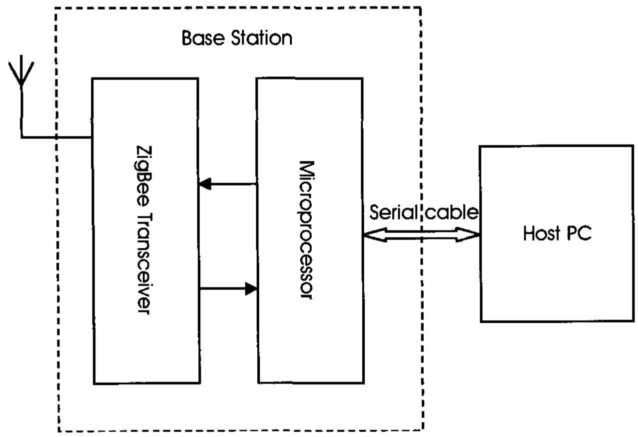


Fig. 5. Block diagram of wEEG Base Station.

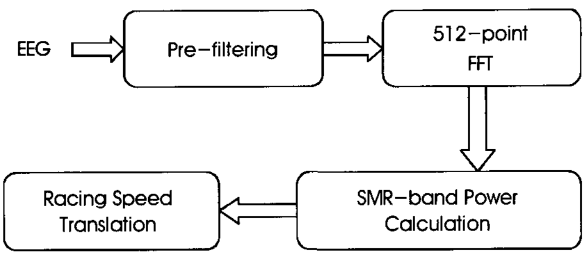


Fig. 6. Procedure for generating feedback parameter.

feedback parameter, the SMR power ratio, will be used for controlling the car's speed using subjects' EEG signals. The $SMR_{threshold}$, measured by undertaking a short measure session before training to calculate the increasing percentage. Finally, we can define the car's speed as the final output feedback parameter:

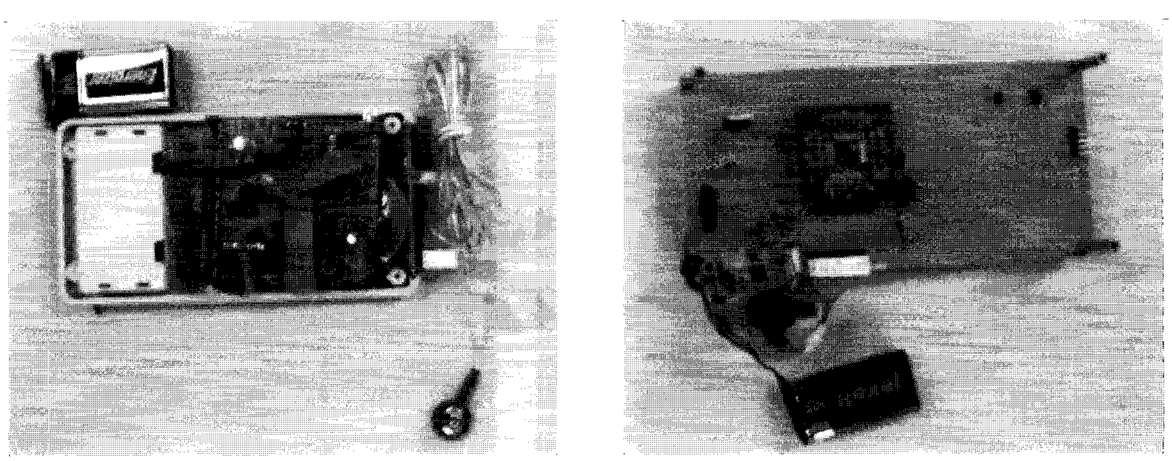
$$V(t) = \begin{cases} 0, & (SMR(t-1) < SMR_{threshold} \\ \left(\frac{SMR(t-1)}{SMR_{threshold}}\right) \times 100, & (SMR(t-1) \geq SMR_{threshold} \end{cases} \quad (2)$$

Where $V(t)$ is the calculated racing speed of the subject in time t and displayed in the VR program on computer scene, and $SMR(t-1)$ is the subject's SMR band power at $t-1$. Since the racing car depends on above SMR band power levels of each subject, it will be helpful to lead the subject to concentrate on the game task instinctively and try to win.

III. IMPLEMENTATION

The temporary version of the wEEG was implemented. The PCB board of mobile station was printed and packed in a case with a PCB antenna. Currently, the base station was developed by using breadboard with an off-the-shelf module. Fig.7 shows the photos of mobile station and base station.

Also, the EEG signal conditioning unit was tested in our laboratory to ensure overall functionality and robustness. In order to verify its performance of gathering human scalp EEG signals, we select 3 seconds of received data from base station to analyze it using Discrete Fourier Transform (DFT) to check



(a) (b)

Fig. 7. Developed wEEG (a) Mobile station (b) Base station.

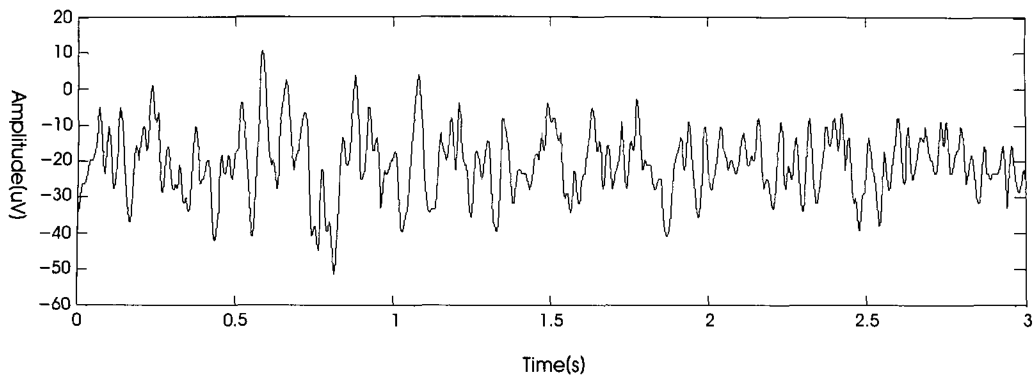


Fig. 8. Received 3 seconds EEG signals from wEEG mobile station.

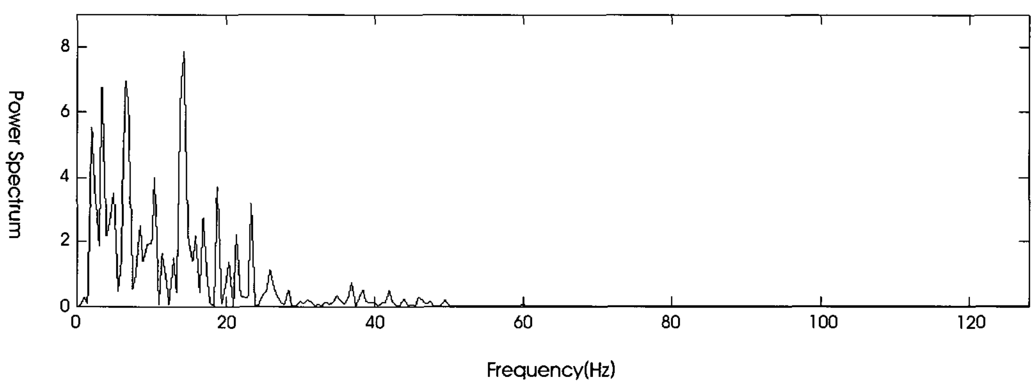


Fig. 9. DFT analysis result of the sample 3 seconds EEG signals.

its frequency components. Fig. 8 shows the received EEG signals from wEEG mobile station, and its DFT analysis result is show as Fig. 9.

We developed a simple virtual reality environment for the attention enhancement training, which was a car racing game liked program. In this program, each single second EEG signals are processed by DFT firstly to get their power spectrum, and then the powers of the EEG components (Alpha or Beta) are translated into control signal directly. So the changes of EEG component power value will be always visible and will correspond to the speed or position of the virtual car. In this way, subjects are getting his or her own feedback about the current power value (or proportion) of the EEG components continually. Especially, in order to improve the interest of subjects, we adopt a racing mode to stimulate the subjects to get more attention during training. There are two racing car in the program. One is controlled by a subject, while the other one is controlled by computer or another subject. If a subject races with computer, the speed of the computer controlled car will be randomly increased referring to the subject's speed. And it is possible that two subjects race each other in our training system. In this case, two racing cars are controlled by two subject's EEG component parameters respectively.

Fig.10 shows the user interface of an example program. There are two racing cars in the middle of computer scene.

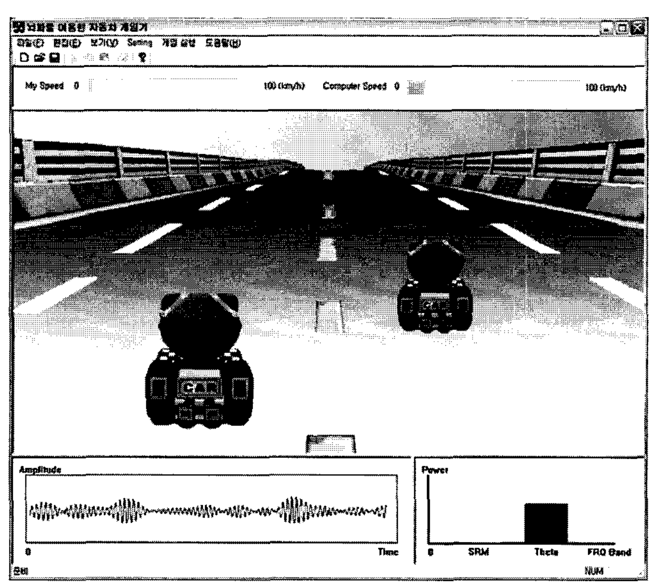


Fig. 10. User interface of the virtual training program.

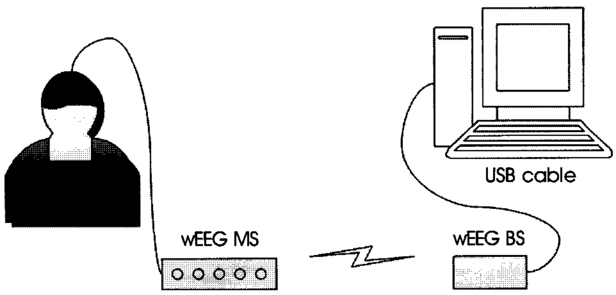


Fig. 11. System hardware configuration.

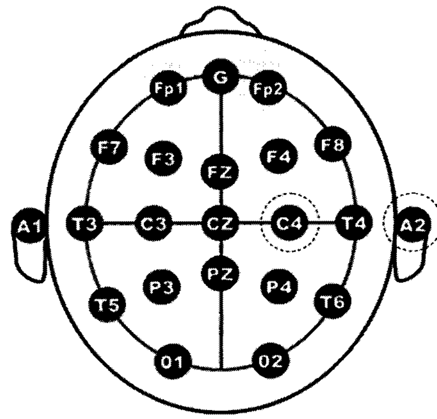


Fig. 12. Overview of international 10-20 electrodes system.

One is controlled by the subject's "brain wave", and the other is controlled by computer. If the feedback parameter (e.g., SMR ratio) reaches the appointed threshold, the subject controlled car will speed up, or it will slow down. The speed is defined by Eq. (2). The filtered EEG wave and the ratio of SMR are displayed in the screen's bottom.

IV. EXPERIMENT RESULTS

A. System Configuration

In order to verify the proposed system, an example Neurofeedback system has been built by using wEEG as the EEG acquisition device for attention enhancement training. The SMR ratio was used as the training feedback parameter. The system configuration is shown as Fig. 11. We use a single channel of wEEG. Two electrodes, A2 and C4 of International 10-20 Electrode System are used as shown in Fig.12, which A2 is the reference electrode, and C4 is in the SMR sensitive area. They are used to collect scalp EEG signals.

B. Experiment Methods, Steps and Results

Sixteen healthy volunteers (8 females and 8 males, average age is 27±4 years old) participated in this experiment. These subjects are all university students and none of them had neurological or mental disorders.

In this experiment, three different mental statuses were compared with each other. These are stable status, with Neurofeedback training status and with mental arithmetic task status. The experiment schedule is shown in Fig. 13. In the stable status, the subjects were asked to keep their normal mental state with eyes opened. In the second state, Neurofeedback training program was started and the subjects were encouraged to complete the game task in two minutes. And then, the subjects would take a rest to recover their common mental state. The rest time might be varied and commonly was around five minutes. In the last step, the subjects were asked to do some mental arithmetic with provided problems in two minutes to check their SMR changes. There were no feedbacks shown on the screen for subjects. During this experiment, all

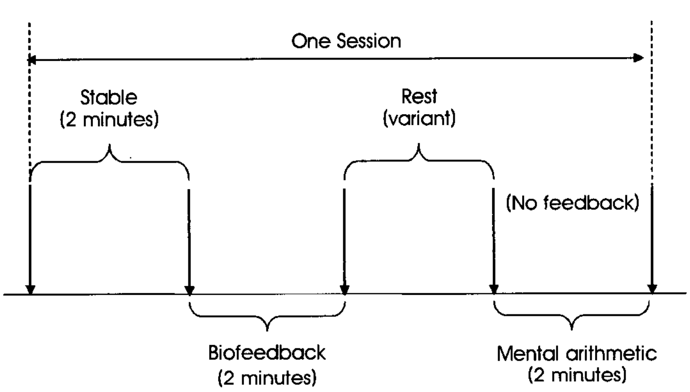


Fig. 13. Experiment schedule.

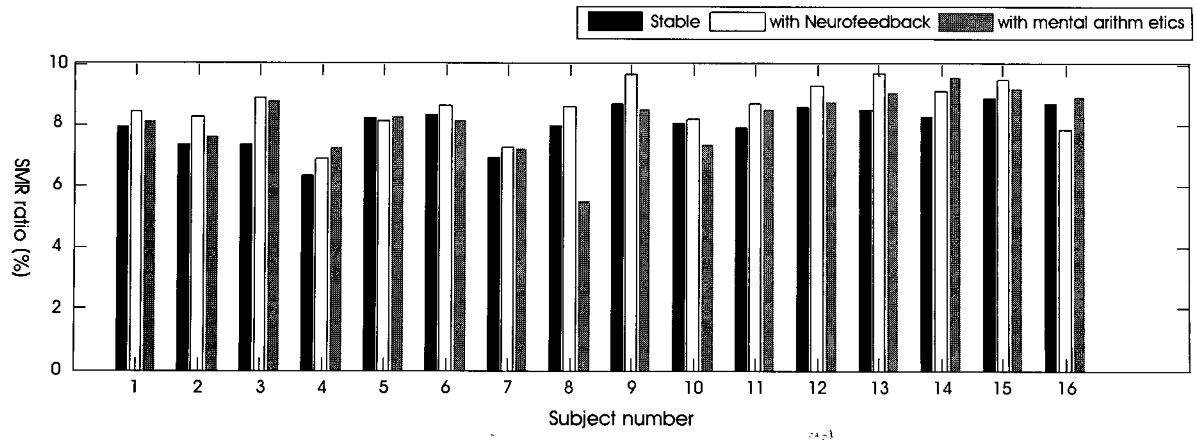


Fig. 14. Average SMR power ratio histogram of each subject.

of the subjects were asked not to move their bodies to minimize the movement artifacts.

We compared the SMR ratio of the 3 different mental states with each other. Fig. 14 shows the average SMR power ratio histogram of every volunteer in 3 different mental states. The detailed comparison results are introduced in Table 3. 87.5% subjects (except subject 5 and 16) had a higher SMR power ratio in Neurofeedback training state than that in the stable state, and the average increasing rate was 0.712%(±0.3694%). In comparison with the mental arithmetic state, there was about 0.703%(±0.8154%) increasing rate for 75% subjects (except subject 4, 5, 14 and 16). There was about 0.513% (±0.4495%) increasing rate for 75% subjects (except subject 6, 8, 9 and 10) in mental arithmetic state VS stable state. In Table 3, the increasing rate of every comparison was calculated by using the data of successful increased subjects (the grey fields indicate the failed subjects), and average SMR power ratio was computed by using the data of all subjects. Here, in

Table 3. SMR power ratio of every subject in three different mental states
(State 1, 2, 3 indicates the stable, with Neurofeedback training, mental arithmetic state respectively).

States / Subject #	State 1 (%)	State 2 (%)	State 3 (%)	State 2 VS 1 (%)	State 3 VS 1 (%)	State 2 VS 3 (%)
1	7.90	8.40	8.07	0.50	0.17	0.33
2	7.35	8.26	7.61	0.91	0.26	0.65
3	7.34	8.88	8.76	1.54	1.42	0.12
4	6.35	6.88	7.25	0.53	0.90	−0.37
5	8.21	8.13	8.26	−0.08	0.05	−0.13
6	8.30	8.64	8.14	0.34	−0.16	0.50
7	6.95	7.27	7.19	0.32	0.24	0.08
8	7.96	8.59	5.49	0.63	−2.47	3.10
9	8.69	9.64	8.51	0.95	−0.18	1.13
10	8.05	8.18	7.34	0.13	−0.71	0.84
11	7.91	8.68	8.48	0.77	0.57	0.20
12	8.59	9.27	8.74	0.68	0.15	0.53
13	8.48	9.70	9.04	1.22	0.56	0.66
14	8.29	9.10	9.54	0.81	1.24	−0.44
15	8.85	9.49	9.20	0.64	0.35	0.29
16	8.68	7.86	8.92	−0.82	0.24	−1.06
Average (%)	7.9938	8.5606	8.1588	0.7121	0.5133	0.7025
Standard deviation (%)	±0.6910	±0.8030	±1.0050	±0.3694	±0.4495	±0.8154

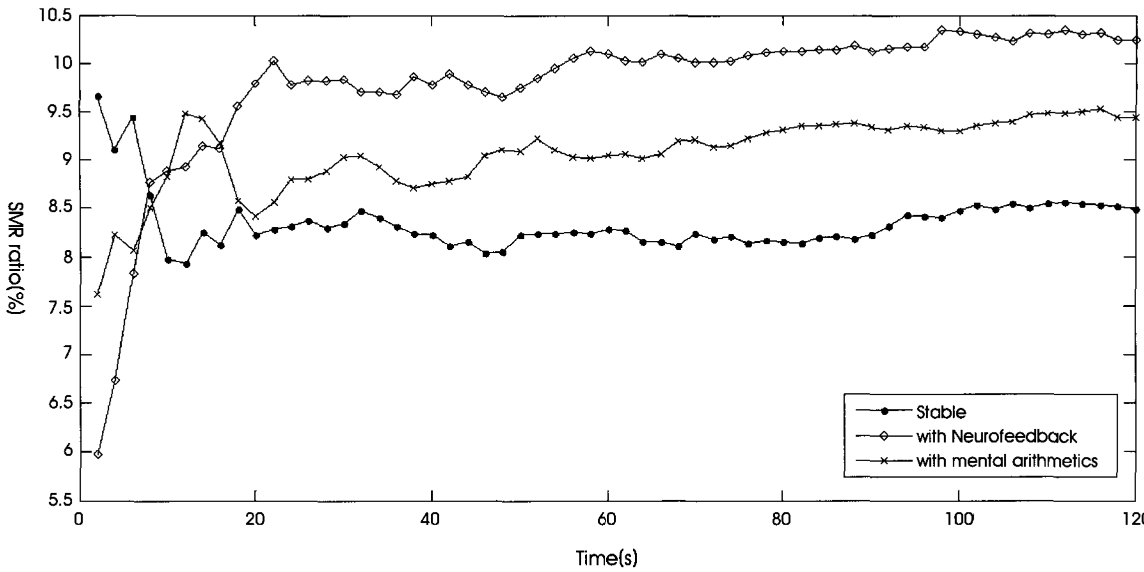


Fig. 15. SMR ratio change curves of 3 statuses (subject 3).

comparison with stable state, we can find that the subjects in Neurofeedback training state had a higher increasing ratio and lower standard deviation than in mental arithmetic state, and Neurofeedback training had more subjects increased their SMR power ratio that mental arithmetic. It means that Neurofeedback with virtual environment makes subjects to pay attention more easily and efficiently.

Fig. 15 shows a two minutes SMR ratio change curves of one subject in the three different mental states. The SMR ratios in this figure were calculated in each 2 seconds (512 sample points). We can find that SMR ratio in Neurofeedback training state was the highest in these 3 different mental states after 20 seconds, and the SMR ratio in mental arithmetic state was higher than that in stable state after 20 seconds.

Since this study aims at developing such a portable wireless EEG system for Neurofeedback, we implemented the developed wEEG to build a prototype system for attention enhancement training by using SMR ratio as the training parameter. Though enough experiments have not been done until now, however, our current experiment results show that 87.5% subjects' SMR power ratios have been increased in their training states with our program.

V. CONCLUSION

In order to develop a portable and convenient Neurofeedback system, a set of tiny 2-channel wireless EEG acquisition device using ZigBee named wEEG has been designed in this paper. A biofeedback training program with virtual reality environment has also been developed. Several experiments were done to evaluate wEEG and biofeedback systems. Extensive experimental results showed that our proposed system was helpful to enhance/inhibit EEG components for EEG biofeedback training. We hope that the proposed portable system can offer an easy and powerful tool for Neurofeedback. By using the tool, users can create flexible treatment programs at home.

Next, we are planning to do more experiments to confirm our system. Our further interests focus on developing more interesting and more flexible training programs by using wEEG, such as developing a PDA interface for wEEG for real time Neurofeedback training, and expending the wEEG mobile station with auditory feedbacks.

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