# The Inhibition of High Load Task on Individual Cognition：A Functional Near-Infrared Spectroscope Study

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**Research**

**Keywords:** functional near-infrared spectroscopy (fNIRS), cognitive load, N-back task, prefrontal cortex (PFC)

**Posted Date:** May 11th, 2021

**DOI:** https://doi.org/10.21203/rs.3.rs-494113/v1



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# Abstract

**Background:** Cognitive load plays a vital role in human cognitive activities, and effective measurement and intervention of cognitive load can improve learners' learning effect. As a new method of measurement, physiological measurement can show the neural mechanism of cognitive overload. MRI and EEG, as the first physiological measurement methods, have made great contributions to the related research of cognition，but they have unavoidable flaws to a certain extent. As a new physiological measurement method in recent years, fNIRS can effectively avoid the influence of the above equipment on the experiment. This study uses fNIRS to measure cognitive load with the N-back classic paradigm, aiming to explore whether the sensitivity of the prefrontal area to the task and the difficulty of the task will affect the cognitive load of the individual.

**Results:** Through the GLM model to concretely analyze the brain activation area and use repeated measurement analysis of variance to compare behavioral data, it can be concluded that the prefrontal cortex can be effectively activated under the stimulation of work tasks. In a certain range, the prefrontal lobe activation becomes more obvious with the increase of cognitive load, but when the cognitive load exceeds the maximum limit that the prefrontal lobe can handle, the prefrontal lobe will be in a negative activation state.

**Conclusion:** These results suggest when the task load is appropriate, the PFC can be most effectively activated for working memory processing. Therefore, learners should be analyzed in teaching activities so as to choose appropriate teaching content to ensure the maximization of teaching effect.


# 1 Introduction

## 1.1 Cognitive load theory and measurement

Since the concept of cognitive load came into being, it has attracted many researchers to study the process of its generation. With the deepening of research, researchers began to explore how cognitive load affects information processing and problem solving, and thus put forward the cognitive load theory. In order to improve learning effect by reducing cognitive load, objective measurement and effective intervention of cognitive load are needed.

As the most complex organizational structure of the human body, every activity is directly or indirectly under the control of the brain. Among them, PFC is considered to be the core region for processing many advanced cognitive abilities(Miller & Cohen, 2001), and the increase and full load of cognitive load must also produce corresponding changes in the brain. As one of the most important organs, the brain’s internal tissue transformation cannot be observed by experimental dissection or other operations. we need to use relevant instruments to concrete the internal structure of brain. With the emergence of MRI, EEG and other hypercanning instruments, physiological measurement as a new way to measure the neural mechanism has been gradually favored by researchers. (Lin & Zhang, 2017). However, due to the technical and cost limitations of hyperscanning equipment, its application in the field of education is still very rare. In this study, we would like to use the hyperscanning instruments to supervise the variable of the subjects' brain when they are doing the memory tasks. Then, it can be compared to the field of education to explore the physiological state of the cognitive load acquired by learners in the learning process and To provide more divergent ideas for the teaching intervention measures.

Cognitive load is an important factor that affects the learning effect of learners in the learning process. Sweller put forward the cognitive load theory (CLT) for the first time after a detailed analysis of cognitive load. CLT believes that cognitive load can be divided into internal cognitive load, external cognitive load and associated cognitive load(Sweller, 1994). There are three cognitive load measurement methods accepted by researchers at present: subjective measurement, task performance measurement and physiological measurement(F. Paas, E. Tuovinen, & Tabbers, 2003). Sweller measured cognitive load based on the difficulty level of the learning material and the learner's performance results. On this basis, Brunken believes that analyzing the correlation between learners' behavioral changes, physiological changes and learning process is also one of the objective and indirect methods to measure cognitive load, and proposes a dual-task analysis method(Brunken, L. Plass, & Leutner, 2003). One of the above two measurement methods is based on the external behavior of learners to complete the task; the other is based on the multi-dimensional self-report of learners. The former method is not widely applicable due to the limitations of the subject and the influence of task introduction on the learning process of learners. The latter method will affect the objectivity of the results because of the subjective judgement. In order to avoid the disadvantages of the above two methods, researchers are interested in physiological measures. Tang et al. tested the cognitive ability of Alzheimer's patients through EEG and evaluated it by stepwise multiple regression(Tang et al., 2001).With the help of MRI, Li explored the relationship between the development of cognitive ability and the characteristics of brain structure and function, bringing enlightenment to the cognitive development of children(LI & LI, 2010).

### 1.2Functional NIRS as a Highly Flexible Device to measure cognitive load

Functional near infrared spectral imaging technology (fNIRS) as a new type of hyper- scanning technology, has the advantage of noninvasive, flexible, portable. It is a non-invasive, real-time monitoring of local tissue blood oxygen saturation (rSO2) optical imaging technology. It has attracted the attention of more and more experts at home and abroad, and has been used in psychology, verbal, cognitive function, executive ability, clinical fields and other fields. It can be used for age groups from infants to the elderly. Compared with other neuroimaging technologies, fNIRS imaging has greater potential. Originally used in biomedics, the relatively high transparency of biological tissue open an "optical window" in the near-infrared region of the spectrum to allow enough photons to be transmitted to help doctors perform clinical examinations(Jobsis, 1977). Ferrari has for the first time applied this technique to quantitative measurements of changes in oxygen levels in the brain, which can be used to determine brain activity(Ferrari, Giannini, Sideri, & Zanette, 1985).

With the continuous development and progress of technology and the continuous crossover between disciplines, fNIRS technology has been applied in the fields of psychology, sports and education because of its high elasticity to body movement and good tolerance to electromagnetic noise. Bai et al. adopted the emotion interference method and found that the dorsolateral prefrontal lobe was not involved in the processing of emotion and behavior inhibition, and believed that the prefrontal lobe was not the key brain region of emotion and behavior inhibition(Bai et al., 2016). Emotion, as a human's behavioral response to objective things, will affect people's processing of information. The appearance of negative emotions will have an impact on working memory, and increase the difficulty of the task and increase the workload, which will reduce the impact of negative emotions(Liu, 2017). Because of its size and non-invasive of the experiment and its mobility, it is feasible to introduce the technology into the field of education. As a new way of teaching, the effective combination of educational games and fNIRS technology can enable researchers to continuously improve the connection between educational games and learning science according to the brain imaging results of learners when using educational games(Kesler, Sheau, Koovakkattu, & Reiss, 2011; Noah et al., 2015; Pei, Shang, & Zhou, 2017; Witte, Ninaus, Kober, Neuper, & Wood, 2015). N-back paradigm is a classic paradigm of working memory task in psychology, which is used by many researchers to study cognitive load(Owen, McMillan, Laird, & Bullmore, 2005; Song, 2011). Based on this paradigm, measurements of the prefrontal cortex not only reveal an interaction between emotion and cognition(Tseng et al., 2018), but also provide hemodynamic evidence that women can master verbal working memory tasks faster than men(Gao, Zhang, Luo, Liu, & Gong, 2016).

However, few researchers have used this technique to measure cognitive load. With the help of fNIRS technology, this study hopes to explore the brain changes of subjects under different states of cognitive load, that is, the activation of related brain regions when cognitive load is overloaded. We hypothesized that the working memory task elicited prefrontal activation and that it changed with difficulty.

## 2 Results

# 2.1 Behavioral Results

The correct rate and reaction time of all subjects in N-back task were statistically analyzed, and the following results were illustrated in Fig. 3.

This shows that when the load factor is 1 or 2, almost all subjects can easily complete the given task, but when the difficulty of the task increases again, the accuracy fluctuates greatly (M = 75.67% ±1.79%, SD = 6.9%), and the reaction time fluctuates at a higher level (M = 735.43 ± 26.16, SD = 101.33). The accuracy and reaction time of different load factors were analyzed by repeated measurement analysis of variance. According to Bartlett's spherical test, $F_a$=100.63,p = 0 < 0.05 ; $F_b$= 30.21, p < 0.05, the difference of the influence of the three load factors on accuracy was statistically significant.

# 2.2 Brain Activation Results

Using NIRS_KIT plug-in to estimate the parameters of N-back tasks with different load factors based on GLM model and conduct a single sample t-test. A positive t-value indicates positive activation, while a negative t-value means negative activation(Rodrigo et al., 2014). Draw the following thermal map in Fig. 4 according to the t value of each channel(Hou et al., 2021).

The activation of the other 36 channels except CH1 CH2 CH7 CH8 CH13 CH17 CH18 CH19 CH24 CH26 CH27 CH32 CH37 CH43 CH47 CH48 was more significant when N = 1 was used. Only six channels of CH2 CH8 CH13 CH17 CH37 CH47 showed negative activation, while all the other 46 channels showed positive activation. When the load factor was increased again, CH9 CH28 CH29 CH36 CH38 and CH39 turned negative compared with N = 1. This shows that when carrying out working memory related tasks, properly increasing the difficulty can effectively activate PFC, to promote its working memory processing; When the difficulty coefficient of work task is too high, exceeding the temporary memory limit that PFC can handle will cause negative activation of PFC and lead to cognitive overload(Bahmani et al., 2019).

Using the NIRS_SPM plug-in in Matlab(Ye, Tak, Jang, Jung, & Jang, 2009) to build a 3D model of the subject's brain based on 3D positioning and MNI coordinates(Morais, Balardin, & Sato, 2018; Singh, Okamoto, Dan, Jurcak, & Dan, 2005). Independent sample t-test and paired sample t-test were performed, and the 3D model activation map of the brain was drawn and shown in Fig. 5.

According to Brodmann area, when subjects performed low-load tasks, the posterolateral prefrontal cortex was significantly activated. During moderate load, the posterolateral prefrontal cortex and frontoorbital region were significantly activated at the same time. When they carried out high load tasks to achieve cognitive overload, the activation areas of posterolateral prefrontal cortex and frontoorbital region decreased.As can be seen from Fig. 5 (d), when the difficulty of the task increased, the subjects mainly showed a state of inhibition in the left posterior dorsal cortex, which was basically consistent with the above-mentioned thermal map.

# 3 Discussion

In this study, fNIRS technology was used to collect and analyze oxygenated hemoglobin under different load factors through N-back task, and the following conclusions were obtained: When individuals perform N-back tasks, they can activate the prefrontal cortex(Bahmani et al., 2019). The activation of prefrontal cortex can help the processing of short-term memory, and the degree of brain activation varies with different difficulty tasks(Herff et al., 2014). Compared with low-load tasks, when the difficulty of the task is properly improved within the range of individual ability, the prefrontal cortex can be effectively activated and the ability and efficiency of dealing with short-term memory can be improved; when the task is so difficult that the individual reaches cognitive overload, the prefrontal lobe of the brain is in a state of inhibition(Bahmani et al., 2019).This shows that within a certain range, the activation area of the prefrontal lobe of the subjects is positively correlated with the difficulty of the task. However, when the difficulty of the task exceeds the maximum that the individual can bear, the activation area of the brain is negatively correlated with the difficulty of the task(Ayaz et al., 2012; Jiao, Bai, Chen, & Li, 2013).

The purpose of learning is to acquire knowledge, but the generation of cognitive load in the process of learning is unavoidable. According to the cognitive load theory, scholars have put forward a series of methods and measures: some of these measures start from the simplification of teaching materials, some from the optimization of teaching activities, in order to reduce learners' external cognitive load or related cognitive load(Mayer & Moreno, 2003; Mayer & Moreno, 2010; F. G. Paas & Van Merriënboer, 1994). Through the academic level and other conditions, we can find that these measures are effective, but what is the reason for this effectiveness, the researchers are unable to explain clearly. To introduce the above conclusions into the field of pedagogy, teachers need to understand the inherent level of students before class in order to make appropriate teaching design. In this way, they will not choose the easier teaching content, nor the more difficult content that is difficult for students to master, so as to activate the learners' brain PFC to process the learning content to the maximum extent. In addition, when learners' cognitive load is overloaded, teachers usually choose to let learners take a rest to reduce their cognitive load. Through the above neural mechanism, the conclusion of this study is that when learners reach cognitive overload and their PFC region is inhibited, if effective external intervention measures are adopted to promote brain reactivation, learners' cognitive load may be reduced more efficiently.

With the continuous development of learning science, pedagogy and psychology have been intersecting and merging. Based on the results of this study, we can provide strong evidence for some psychological measures to reduce learners' cognitive load that we have proposed before. For example, teaching design combined with music(Owens & Sweller, 2008) or emotion regulation are effective for the improvement of cognitive ability(Ochsner & Gross, 2005). If the prefrontal cortex of learners is more significantly activated after these external interventions than before the intervention, we can consider the intervention to be effective and feasible.

## 4 Methods And Materials

# 4.1 Participants

Eighteen healthy adults between the ages of 20 and 26 took part in the experiment, all from a university in Shanghai. Three subjects had to be excluded because of the loss of fNIRS signal. Therefore, the final sample N = 15, including 11 boys and 4 girls (M = 22.78, SD = 1.73). Subjects have no current or previous mental, physical or neurological disorders and are right-handed and have normal corrected or naked vision. All subjects signed the informed consent before participating in the experiment to understand the whole experiment process, and were given certain remuneration after the end of the experiment.

# 4.2 Experimental Design

The experiment uses a block design, in which subjects are required to perform the variable N-back task in the same environment. Different load factors (n = 1,2,3) were used to repeat the experiment, and the difficulty of the level gradually increased with the increase of the load factor. At the beginning, the subjects can practice freely and choose the level by themselves. The experiment can be carried out after the correct rate of the first level is more than 80%.After the exercise, the experimenter will help the subjects to wear and correct the instrument, and conduct the test on the machine until all channels are in good contact with the experiment. The flow chart of the experiment is shown in Fig. 1 below. There is a baseline level time of 40 seconds before the task starts. The subjects were given three different difficulty stimuli and repeated three times over the course of the experiment, each of which lasted 60 seconds. A 30-second rest period after the stimulation is completed ensures that the individual's brain returns to its baseline level(Dale, 1999).

# 4.3 Fnirs Recording

All the subjects' imaging data were collected by the 52-channel ETG-4000 device(Hitachi Medical Co., Japan), which has the advantages of simple operation, fast image acquisition, high signal-to-noise ratio and more accurate data. The device penetrates the skin by emitting two wavelengths of near-infrared light (695 and 830nm) that are absorbed or scattered within tissues. Therefore, the relative concentration changes of oxygenated hemoglobin and deoxygenated hemoglobin in the brain can be determined based on the diffuse reflected light. The distance between the photodiodes installed in the ETG-400 is 3cm, and the sampling frequency of fNIRS is set to 10Hz. In order to measure the prefrontal lobe of the subjects and evaluate changes in hemodynamic responses, a 3×11 multi-channel cover plate was used to fully cover their prefrontal lobes. There are 17 Emitters and 16 Detectors on the cover, as shown in Fig. 2a, which are arranged according to the international 10–20 EEG system to form 52 detection channels, as shown in Fig. 2b(Jasper, 1958). Subjects who successfully wear the device are shown in Fig. 2c.

## 4.4 Fnirs Data Analysis

# The fNIRS data satisfies the general linear model (GLM), and the actual data matrix and the experimental design matrix satisfy Y = Xβ + e(Gratton, Toronov, Wolf, Wolf, & Webb, 2005), so the actual signal is shaped like an irregular shock wave. During the scan, subjects were asked to stay awake during the rest period, not to think as much as possible and empty their brains. Concentrate on completing the N-back task in the ongoing phase of the task, and collect the brain location information of the subjects after the completion of the task. Due to the difference of the subject's brain, the position of the channel will also change to a certain extent, so it is necessary to use a ruler and a

dotting device to locate the probe worn by the subject(Lancaster et al., 2007; Morais et al., 2018; Singh et al., 2005). The original data obtained by fNIRS are photoelectric signal data. According to the preset experimental paradigm, the original data are imported into Matlab,. Based on the modified Beerlambert law (Kocsis, Herman, & Eke, 2006), the photoelectric signals are converted into computable oxyhemoglobin (oxy-Hb), deoxyhemoglobin (deoxy-Hb) and total hemoglobin (total-Hb) by using NIRS_SPM(Ye et al., 2009) and NIRS_KIT(Hou et al., 2021) toolboxes. The motion artifacts were eliminated according to the blood oxygen dynamics curve and wavelet transform(Jang, Tak, Jang, Jung, & Ye, 2008). Because $HbO_2$ has higher signal amplitude and signal-to-noise ratio, it is used to characterize the level of brain activation(Strangman, Culver, Thompson, & Boas, 2002).

## Declarations

### Ethics approval and consent to participate

This research was approved by the Ethics Committee of East China Normal University. Before starting the experimental task, participants received information about the purpose of the study, the task, and its duration and gave their written informed consent.

### Consent for publication

Not applicable.

### Availability of data and materials

The datasets used and analyzed during the current study are available from the corresponding author on reasonable request.

### Competing interests

The authors declare that they have no competing interests.

### Funding

Not applicable

### Author's contributions

CMZ and XHS conducted the experimental task and analyzed the data. CMZ wrote the manuscript. CMZ, CQY and XHS designed the experimental task. All authors read and approved the final manuscript.

### Acknowledgements

Not applicable

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# Figures

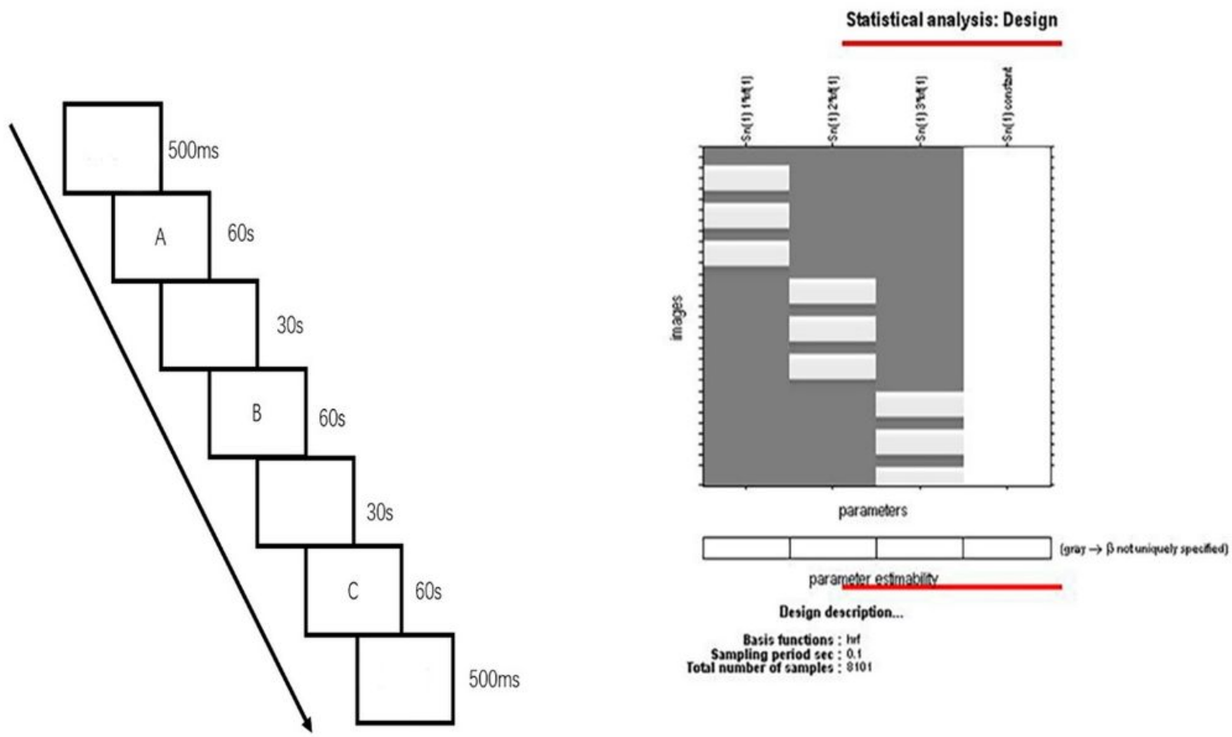
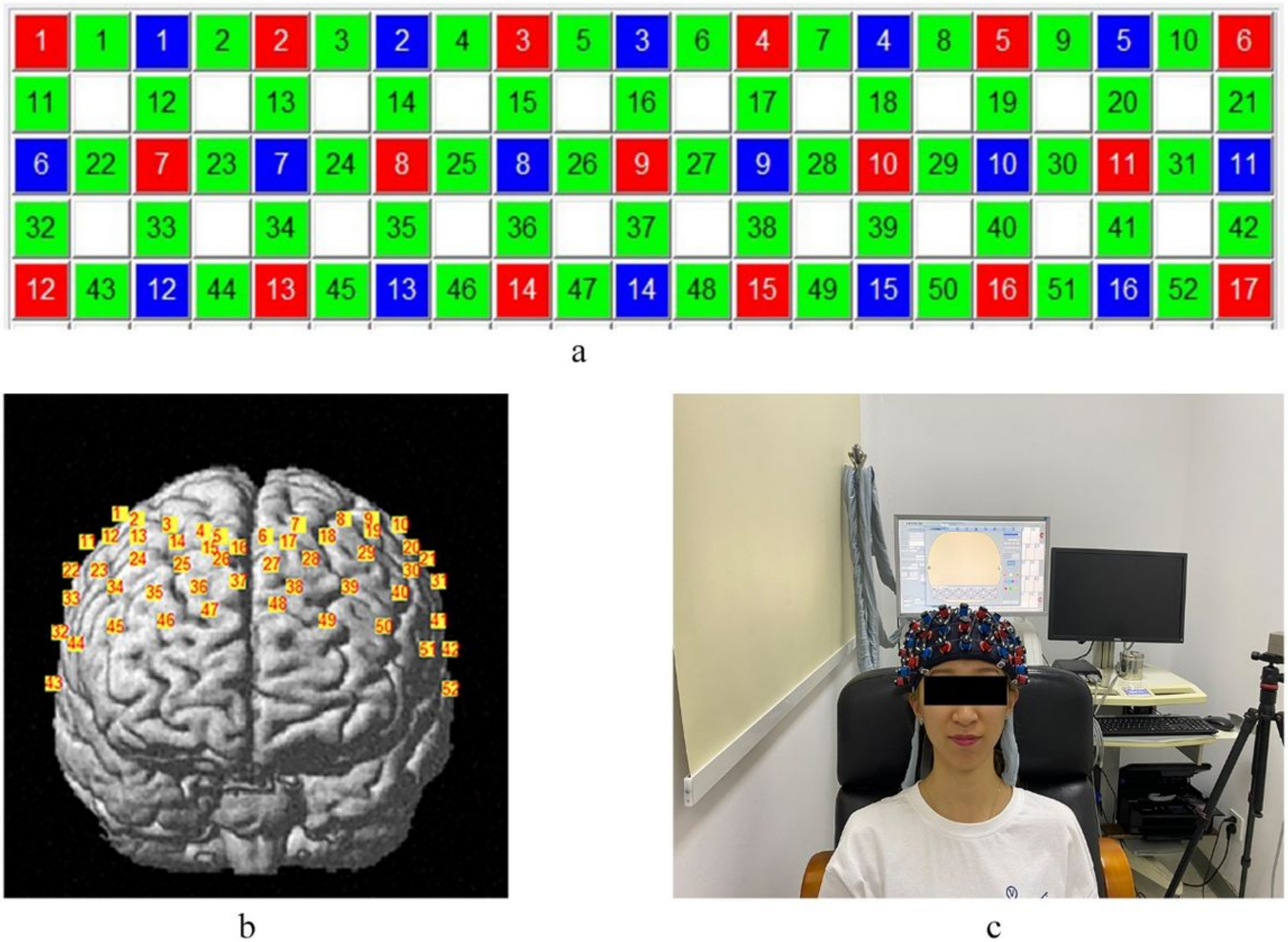


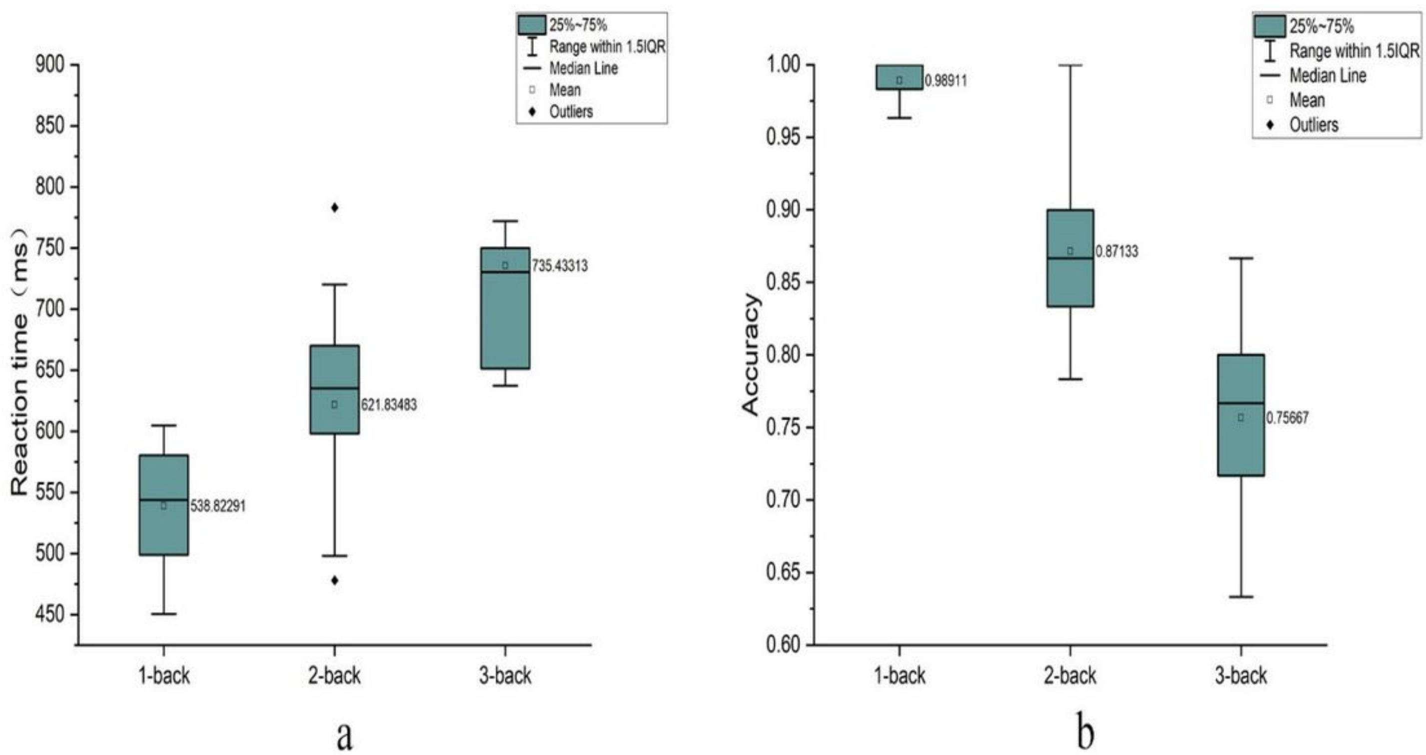

**Figure 1**

Flow chart of experiment



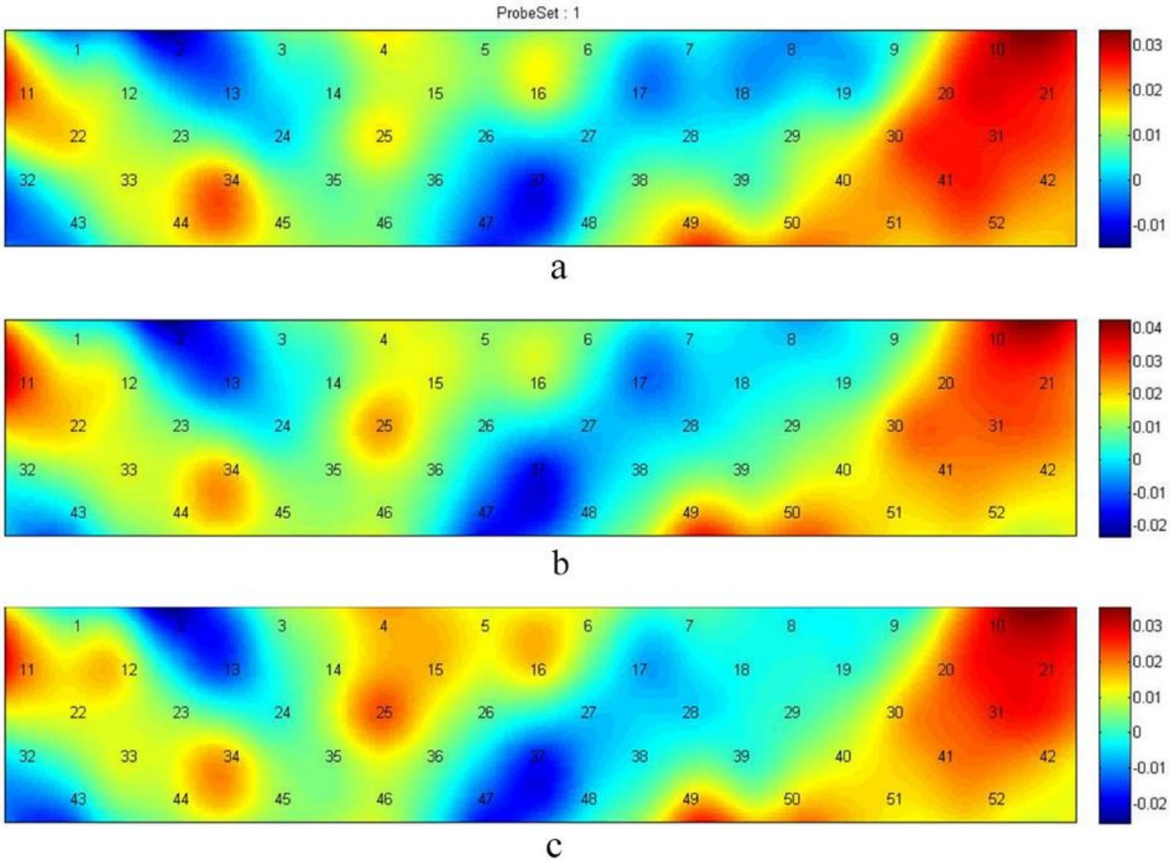

### Figure 2

The arrangement of 52 probes, of which red are the emitters，blue are the detectors and green are the channels(a).The location of the 52 channels on the subject’s scalp(b). Subjects who successfully wear the device(c).



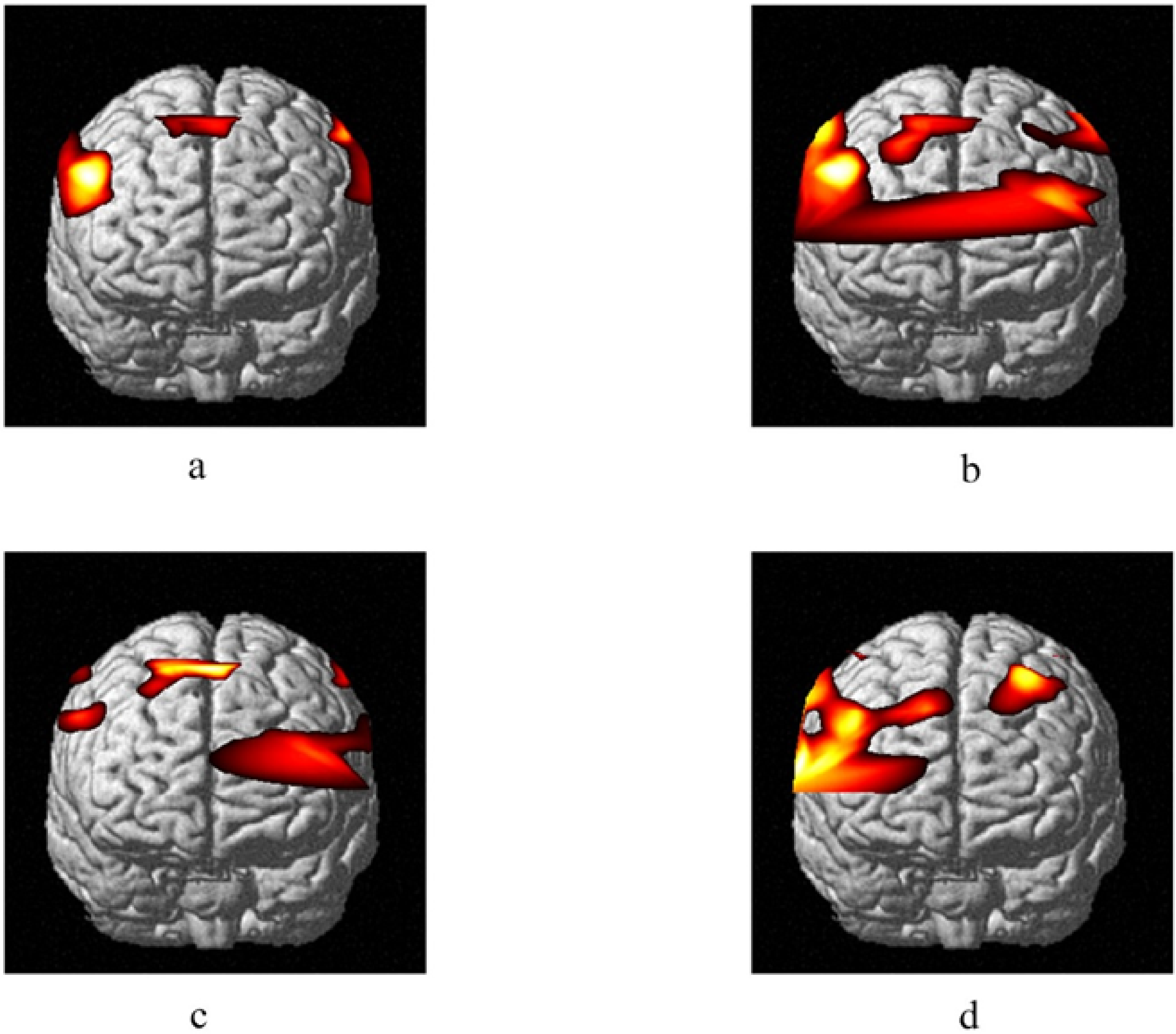

## Figure 3

behavior data




## Figure 4

(a)(b)(c)respectively corresponds to the load coefficient N=1,2,3. Each channel is presented on the same 2D plane, depending on the t-value. The color ranges from blue to red. The closer the color is to blue, the less obvious the channel activation is. On the contrary, the closer the color is to red, the more significant the channel activation is.




### Figure 5

The activation of the PFC in the N=1 state compared to the resting state(a). The activation status of PFC increased when N=2(b). The negative activation of PFC increased at N=3(c). There was a big difference between N=2 and N=3 in the left prefrontal region(d).