A Brief Review on Development for Motion Artifact Correction and Global Interference Removal for Human Functional Near-Infrared Spectroscopy

Jiang Jin[1] Jiao Xuejun[1] Pan Jinjin[1] Xiao Yi[1] Jiao Dian[2]

[1]*Key Laboratory of Human Factors Engineering, China Astronaut Research and Training Centre, Beijing* 100094, *China*

[2]*College of Precision Instrument, Tianjin University, Tianjin* 300072, *China*

Abstract The functional near-infrared spectroscopy (fNIRs) is a new convenient non-invasive optical imaging technology to explore human brain activity through cerebral hemodynamics within human brain. However, the fNIRs signal is susceptible to interference induced by human relative motion and physiological activity. The interference can damage the quality of signal, so it is important to develop approaches to eliminate the motion artifact and physiological interference from fNIRs signal. Brief introduction to current development of fNIRs signal processing techniques to correct the signal contaminated by motion artifact and physiological interference is given. The current problems of fNIRs techniques, some promising research fields and the correlation between fNIRs and functional magnetic resonance imaging are discribed. A brief conclusion for fNIRs signal processing techniques is obtained.

Key words medical optics; functional near-infrared spectroscopy; physiological interference; motion artifact

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功能性近红外技术的运动伪迹和生理干扰处理方法综述

姜 劲[1] 焦学军[1] 潘津津[1] 肖 毅[1] 焦 典[2]

[1]中国航天员科研训练中心人因工程重点实验室, 北京 100094

[2]天津大学精密仪器学院, 天津 300072

摘要 功能性近红外技术是一种新型无损检测人脑功能性活动的探测技术,该技术监测到的脑功能信号易受到生理活动和人的相对运动的干扰,分别称为生理干扰和运动伪迹,这些干扰的存在严重影响信号质量,因此需要开发消除生理干扰和运动伪迹的信号处理方法。介绍了目前功能性近红外信号的主要干扰源、相应的生理干扰与运动伪迹的去除方法,分析了当前功能性近红外技术存在的问题和可能的发展方向,并重点讨论了功能性核磁共振技术与功能性近红外技术的优劣。最后总结了功能性近红外数据处理方面的发展前景。

关键词 医用光学; 功能性近红外光谱; 生理干扰; 运动伪迹

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1 Introduction

The functional near-infrared spectroscopy (fNIRs) is a non-invasive technology to obtain cerebral hemodynamic response related to brain neural activity, and is a versatile neuroimaging tool with increasing

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作者简介: 姜 劲(1991—),男,硕士研究生,主要从事基于功能性近红外光谱、脑电、心电等多生理参数的脑力负荷、操作者功能状态等方面的研究。E-mail: jiangjin02180018@qq.com

导师简介: 焦学军(1969—),男,博士,副研究员,主要从事生物医学工程、航天环境下的脑力负荷、操作者功能状态以及生物特性等方面的研究。E-mail: jxjisme@sina.com(通信联系人)

acceptance in the neuroimaging community[1]. fNIRs is different from other existing functional brain imaging techniques, *e.g.* functional magnetic resonance imaging (fMRI), electroencephalography (EEG), positron emission tomography (PET) and magnetoence-phalograhy (MEG). Compared to EEG and MEG, fNIRs technique has better spatial resolution through measuring neural vascular response, and temporal resolution of fNIRs is much better than that of fMRI and PET. It can be regarded as a compromise of temporal resolution and spatial resolution to measure brain neural response.

fNIRs utilizes variations in the intensity of the light passing through the brain tissue which indirectly reflects the concentration changes of oxygenated hemoglobin (HBO) and deoxygenated hemoglobin (HBR) in the cerebral blood flow. According to the modified Beer-Lambert law, the concentration changes of HBO and HBR can be calculated. The variations in HBO and HBR of cerebral blood flow are proven to be closely related to the functional neural activity through a sequence of complex coordinated factors including neurons, glia and vascular cells[2]. When a region of the brain is stimulated with an appropriate visual, auditory, cognitive, emotional or motor task, localized cerebral blood response would be activated. The phenomenon is called as neurovascular coupling[3]. fNIRs is a tool available to monitor the cerebral blood changes caused by real brain activation. Moreover, it provides direct measurement of oxygen consumption in brain, which provides a potential way to unveil the mechanism of complicated neurovascular coupling[4].

As for research on fNIRs, prefrontal cortex, visual cortex and motor cortex are regarded as regions of interest. The prefrontal cortex is involved in important processes such as decision making, managing of goals[5] and emotional processing such as empathy processing. Visual function is generally considered to derive from occipital cortex, called as visual cortex. However, some researchers found new things. Nobre *et al.*[6] proposed that the breach of visual expectation engaged the medial orbitofrontal cortex (OFC) as participant was reading, and Hofmann *et al.*[7] found a lower occipital deoxygenation to unpredictable than to predictable words with measurement of medial orbitofrontal cortex during reading with fNIRs devices. Meanwhile, there were also some controversial domains to be studied. Motor function is a promoting direction to be investigated. Piper *et al.*[8] designed a wearable multi-channel fNIRs system and succeeded in outdoor activity freely. They demonstrated the feasibility of fNIRs system for realistic life. Other brain regions are also studied by researchers, but the three regions above are the main concern.

This article aims to introduce the development of fNIRs method and data analysis technique. Many data analysis methods have been applied to the current researches to improve signal quality. The main components of the fNIRs signal are subscribed as table 1. The fNIRs signal is often contaminated with systemic interference, motion artifact and baseline shift. However, not every interference source significantly affects signal quality. It depends on the task and brain region. As we know, there are Kalman filter, wavelet filter, spline interpolation, principle component analysis, independent component analysis, short-separation measurement and correlation-based signal improvement to improve signal quality. It is necessary to explore the suitability of each signal process technique, Brigadoi *et al.*[9] compared different correction methods during a cognitive experiment, aiming to correct low-frequency motion artifact. All of the methods above have been applied to process fNIRs signal, and many researchers proposed new techniques. Gagnon *et al.*[10] put forward a new way using short optode separation and state-space modeling to remove superficial interference and recover brain task-evoked signal.

The choice of signal process techniques should be careful to avoid damage of the data or damage the data as little as possible, and it should depend on the region and task. Hence there exists a demand to summarize previous signal process techniques.

Table 1 Classification of main components in fNIRs signal

Category	Evoked		Non-evoked	
	Neuronal	Systemic	Neuronal	Systemic
Cerebral	Functional brain activity	Change in blood pressure, cerebral blood flow	Spontaneous brain activity	Heart rate, respiration, Mayer wave, very low frequency oscillation
Extracerebral	Autonomic nervous system response	Change in blood pressure, skin blood flow	/	Heart rate, respiration, Mayer wave, low frequency oscillation

2 Techniques for correcting motion artifact

2.1 Source of motion artifact

The signal from brain region is the mixture of hemodynamic response occurring in the gray matter and interference from the brain tissue layers, including scalp and skull[11]. Moreover, fNIRs is susceptible to motion artifacts. Head movement results in shift in the optical coupling between the fiber and the skin, and fNIRs signal suffers a rapid change and fails to record brain activation phase. The motion artifact also affects the baseline value of signal[4]. The noise induced by motion in fNIRs measurement is far greater than the changes caused by other sources, such as tissue and instrument, so it is the first factor to consider. Then there is necessity to have a review of signal processing techniques to acquire high quality signal.

2.2 Techniques for eliminating motion artifact

The general easy approach to deal with motion artifact is to minimize the impact of the artifact by means of obtaining enough trials and simply rejecting stimulus trial by detecting unique change of scale in fNIRs measurement or violating the defined quality criteria of signal[8], while phase rejection does not only reduce the number of trials available and contrast-to-noise ratio of the hemodynamic response function, but also inevitably leads to loss of important information of fNIRs signal.

There are many approaches developed to correct motion artifacts containing fNIRs signal[12]. And it is reasonable to divide the existing techniques into two categories: 1) the methods that detect the motion artifact via additional sensor devices and recover corresponding signal phases; 2) the methods that use algorithms to automatically detect and remove motion artifacts from the fNIRs measurement without additional devices[4].

2.2.1 Category 1 for removing motion artifact

For the category 1, Blasi *et al.*[13] measured accelerated velocity during task to identify the motion artifacts based on the abnormal variation of the standard deviation with an accelerometer. Then they used a recursive least squares adaptive filter to correct the identified motion artifact. Virtanen used an accelerometer to estimate the baseline motion artifacts and corrected it by the way of scaling the amplitude of fNIRs measurement. Robert developed a method to detect the motion artifacts with two source-detector pairs located in the same region, based on the assumption that the short source-detector pair only records motional changes but not the functional hemodynamic changes, then they could obtain the functional hemodynamic changes by the way that the signal from long source-detector pair subtracts the regressor variation from short source-detector pair.

Although the category 1 has been applied to many researches and is regarded as a useful method, there exists more promise in the methods of the category 2. It is better to utilize approaches without additional instruments to detect motion artifact automatically. According to the principle of fNIRs techniques, the features of frequency or amplitude are generally utilized to identify motion artifact.

2.2.2 Category 2 for removing motion artifact

Now there are many successful methods of category 2 applied in the studies. A profound technique is principle component analysis (PCA). The application of PCA aims at separating functional hemodynamic response from fNIRs data. Zhang *et al.* developed a PCA approach to isolate functional response from motion artifact and systemic interference with minimal impact, and Wilcox *et al.* also used PCA approach in functional studies. Brigadoi *et al.* compared PCA method with other methods by filtering a special motion artifact that is induced by participants jaw movement during vocal task. Another one is independent component analysis (ICA) approach which is similar to PCA. Both of them decompose signal into different components, which are statistically independent. Some researchers applied ICA to fNIRs studies. Robertson *et al.* developed an ICA-based method to identify motion artifact and remove it from fNIRs data.

Besides, Cui *et al.* proposed a correlation based signal improvement method (CBSI). This method is based on that motion artifact is induced by head movement causing a positive correlation between oxy-hemoglobin and deoxy-hemoglobin, this phenomenon violates the principle that the correlation between two types of hemoglobin is generally negatively correlated. This finding could be used as a foundation to detect motion artifact. And this method is proven to improve signal quality contaminated by motion artifact.

Wavelet-based filtering is also an effective way to eliminate impact caused by movement. This method decomposes signal into several parts depending on frequency band. And it provided good frequency localization of functional response. Behnam *et al.*[14] proposed a wavelet-based technique for application in fNIRs studies. The wavelet transform removed the wavelet coefficient corresponding to the motion artifact from the fNIRs signal before the modified data was reconstructed. And the result showed great improvement over motion artifact. It is noted that wavelet- based filtering effectively eliminates the effect of regular movement.

Some people hold interest in discrete Kalman filtering to settle motion artifact. According to the Kalman filter theory described by Izzetoglu, it provided optimal prediction of function response from contaminated data with maximum likelihood estimation based on prior knowledge. The application of this method was a recursive process and a 4 order model was recommended by Izzetoglu[15], which ensured stability for the filter. However, it is noticeable that the signal must contain some components without motion artifact and ratio of such components is still unknown. Another similar approach is Winner filter, which is also used by Izzetoglu[16].

Variable standard deviation of fNIRs signal could be utilized to identify motion artifact. Scholkmann *et al.*[17] applied spline interpolation into fNIRs research by means of calculating moving standard deviation. In his research, a cubic spline interpolation function was used to replace period which was considered to be mixed with motion artifact from original data. However, this method suffers from a lack of effective technique to detect motion artifact. If new and reliable techniques for motion artifact detection or a combination application with category 1 techniques are proposed, the spline interpolation will be more prospective[9].

The methods for reducing motion artifact are briefly introduced as above. However, it is difficult to find an optimal technique to deal with all the motion artifacts in fNIRs researches, due to the complexity of motion artifacts. Generally, motion artifacts comprise of different shapes, frequencies and timings. It is hard to reach a comprehensive summary containing a variety of motion artifacts varying from large amplitude change, high frequency to lower frequency and sharp spikes[18]. A feasible strategy is to select a method depending on the main type of motion artifacts presented in the studies. The rare or slight motion artifacts could be ignored. Then it is feasible to develop a stable technique to deal with most common types of motion artifacts in current fNIRS studies, such as blink movement.

3 Techniques for removing physiological interference

3.1 Source of physiological interference

The signals from fNIRs studies are usually degraded by physiological activity, and hemodynamic functional response suffers from the disturbances of cardiac cycle, respiratory and low frequency oscillations. The main source of such interference derives from the physiological interference of superficial layer of the scale and brain tissue. It is usually called global interference. There is evidence that fNIRs measurement is 10 to 20 times more sensitive to hemodynamic changes in superficial layer of the scalp than functional hemodynamic response in brain tissues, depending on the distance between the light source and light detector[18]. And the hemodynamic changes in the skin of the scalp are classified into two categories, non task-evoked changes and task-evoked changes.

The non task-evoked changes are caused by cardiac cycle, breathing activity, blood pressure and Mayer waves, which contribute to 10% of the hemodynamic changes in fNIRs measurement. This type of the physiological interference is stable and statistically independent on brain activation signal, occurring on the superficial skin and deeper brain tissue. However the task-evoked changes are related to blood flow in superficial skin and brain tissue, which overlap with task-evoked brain activation signal, for example, the blood pressure changes rapidly when a participant receives some horrible stimulus. The task-evoked interference is derived from task related blood pressure changes and complex vascular regulation mechanisms[19]. Some evidence demonstrated that the variation in blood pressure can lead to masking brain activation response in fNIRs measurement. However the mechanism of the blood flow in the superficial is hard to explain, due to the fact that skin blood flow supplies energy for the skin and tissue controlled by autonomic nervous system, which is still a challenge to be explored.

3.2 Signal processing techniques for physiological interference

In order to overcome the obstacle of physiological interference, there are several techniques to deal with it. The most common and easiest method to recover true brain signal is block average through averaging signals from a certain number of acquired trials to identical stimuli in time domain. Dommer *et al.*[20] obtained hemoglobin concentration changes by calculating the time course average for HBO and HHT per trial and subject by means of block average. It assumes that physiological interferences are independent on the functional response and comprehensive physiological components are different from each other in phase. The main drawback of this method is that the number of the trial recording must exceed 50.

Another commonly used method is band-pass filtering. This method can remove the heart beat and high frequency contents (f>0.7 Hz) of the fNIRs signal. The lower frequency interference in fNIRs measurement is wiped out by this way carefully, because the frequency band of respiration and Mayer waves is identical to the frequency band of functional response. But this technique is usually used in fNIRs studies to remove high (>0.7 Hz) or very low (<0.1 Hz) frequency interference in the acquired data. In order to reduce the influence of heart rate and breathing activity, a filter was applied to remove frequency components in the range of 0.07~0.13 Hz and 0.2~0.4 Hz by Kaiser *et al.*[21] Naseer *et al.*[22] used a 4th order Butterworth filter with cut-off frequency of 0.1 Hz to remove the interference induced by cardiac activity, breathing and variation of blood pressure. The method is not suitable for extracting evoked brain activation response from fNIRs signal. When removing task-evoked physiological interference by this way, it also removes part of task-evoked brain functional activation. But the band-pass filter, in the application for brain-computer interface, reached its requirement. Naseer *et al.*[22] demonstrated that application of bandpass filter was acceptable for BCI interface with fNIRs device.

Short-distance correction is also an effective technique to eliminate physiological interference. The short source-detector distance method measures the hemodynamic change in the superficial skin on the brain, but less reflects the functional response in the brain. Gagnon *et al.*[10] designed a new short optical configuration with two 1 cm source-detector arrangement to measure systemic noise from the skin on the head, and the measurement worked as a regression to reduce physiological noise and recovered evoked functional response. An important factor for short-distance methods is how to determine the weighting factors to subtract reference channel signal from long-distance separation channel signal. Some methods are proposed to obtain weighting foctor, *e.g.* Zhang *et al.*[23] determined the weighting factor by using adaptive filter.

Two methods based on data-driven approach are introduced to fNIRs signal processing, including PCA and ICA, which can extract useful information from comprehensive signal.

A technique proposed by Zhang *et al.*[24] was applied to determine the major eigenvectors of the physiological interference with the assumption that spatial patterns of system interference consist of main part of the baseline signal, and the corresponding component of baseline signal shows more global and higher energy. The subspace with identified eigenvectors was established, and the obtained fNIRs signal was transferred to the orthogonal subspace, aiming to perform spatial filter. After the process, a localized fNIRs response more significant than original signal was found. Besides, Kohno *et al.*[25] proposed a new temporal ICA to extract system interference from the original signal. With this method, they reconstructed a more localized activation response. Another way to use ICA and PCA was to separate physiological response relating to heart rate, respiration and Mayer waves from the original signal, which is introduced by Markham *et al.*[26]

The method based on wavelet transform is a general way to eliminate the physiological interference. The method decomposes the signal to different components relating to task-evoked response, physiological interference and other unexpected noise at distinct scales. Many people tried to apply wavelet filter to fNIRs signal processing. Lina put forward a new general linear model, which is based on wavelet transform, to separate physiological noise from fNIRs signal, and this technique provided an estimator, which is capable of reconstructing real task-related cerebral response. In order to find optimal estimation of the number of wavelet coefficient for system interference, a method minimizing the minimum description length principle was employed. According to literature, the frequency component of global interference overlapped with cerebral response. The wavelet method could predict hemodynamic response, which is of great advantage over the traditional band-pass filter.

Empirical mode decomposition (EMD) algorithm was also considered by Zhang *et al.* as an effective approach to reduce the influence of system interference of the fNIRs signal. The method used by Zhang *et al.* significantly improved functional brain response by eliminating the physiological interference[27]. EMD algorithm is capable of iteratively decomposing fNIRs signal, which is considered as multi component combination into multiple intrinsic mode functions. In each iteration, it is necessary to remove the highest frequency component until there is only a monotonic trend remained. Although the method based on EMD algorithm is shown as a useful tool to process fNIRs signal, there exist some annoying problems. Mode mixing phenomenon sometimes occurs between the intrinsic mode functions of physiological interference or functional brain response respectively. Aiming to overcome the drawback, two modified methods were proposed based on the EMD algorithm. Torres *et al.*[28] presented complete ensemble empirical mode decomposition with adaptive noise. Nima *et al.*[29] modified the method by means of employing normalized least mean squares technique and recursive least squares technique.

4 Other fNIRs signal processing techniques

All methods above were applied to extract localized functional brain response from the signal and showed different advantages respectively. Then a summary of those methods is necessary to introduce the development of the fNIRs signal processing. It is noticeable that other researchers proposed new methods different from the methods above. Haeussinger *et al.* proposed a filter method to eliminate effect of skin blood flow on fNIRs signal. They identified several reference channels accounting for physiological interference by combination research with fMRI. Then the channels of region of interest were averaged and subtracted from the mean of reference channels. The result showed improvement on the brain activation response.

The research on methods for improving the quality of fNIRs signal is a promising direction to study. Physiological interference is comprised of many components, so it is a promising field to develop techniques to extract other information from fNIRs signal such as heart rate, change of blood pressure and respiration.

5 Future direction of fNIRs techniques

5.1 Use of extracerebral interference of head

The extracerebral component of the fNIRs signal is predominantly apparent on the forehead, but the current researches focused on how to correct it. It is possible to unveil the correlation between the extracerebral component and brain functional response. Kirilina *et al.*[30] measured the bold effect caused by extracerebral component. The result suggested that the bold effect reflected the change in vessles. It was found that blood pressure changes were responsible for the changes of extracerebral component. Such effect was also corresponding to occurrence of the task. And the superficial vessels are controlled by the sympathetic nervous system. It is a good indicator of the physiological changes of the individual, which reflects autonomous nervous system. Haeussinger *et al.*[20] proposed an assumption that there is correlation between the inter-task variation and exracerebral component. How to use the changes of the extracerebral component of the fNIRs signal is a promising field in future.

5.2 Development of real time signal processing techniques

With the development of fNIRs signal processing techniques, more advanced fNIRs instruments will be provided and more information from fNIRs signal can be obtained. In addition to the techniques for the motion artifact correction and physiological interference correction, the algorithm and processing tools are required to meet the requirement of real-time processing speed and accuracy. Although Naseer *et al.*[22] made use of two features of the fNIRs signal to develop the real-time brain-computer interface, the method for signal processing based on frequency-band filter is simple. The real-time signal processing technique for fNIRs signal is still an unknown field.

5.3 Application for brain-computer interface

The brain-computer interface offers human a method to control robot and machine by means of detecting specific brain functional response corresponding to specific cognitive task. In recent years, the fNIRs measurement is used to establish brain computer interface. Kaiser *et al.*[21,31] adopted fNIRs measurement to develop the brain computer interface in the motor imagery task. The inherent time delay of hemodynamic brain functional response caused a challenging work of fNIRs signal for brain computer interface. On the other hand, how to select appropriate feature from fNIRs and classification method is an important problem. However, the interpretation of fNIRs signal is a way to gain insight into the mechanism of the brain activity due to identification of specific brain functional response corresponding to specific behaviors.

5.4 Explanation between deeper neuronal activity and systemic interference

The high sensitivity of fNIRs measurement to hemodynamic fluctuations and oscillations provides an opportunity to gain a more explicit insight into the relationship between the neuronal and systemic interference and the physiological condition of the resting state. In combination research with fMRI, the cardiac fluctuation overlapped with the activity with medulla oblongata and brainstem when participant was at resting state[31]. Due to physical limitation of the fNIRs principle, the fNIRs measurement could not acquire more information from deeper brain region, such as brainstem. The interpretation of hemodynamic fluctuations and oscillations at resting state is probably a way to gain information of the deeper brain component.

5.5 Emotional effect of fNIRs signal

As we all know, there exists distinct effect caused by emotional task in fNIRs researches. And some reseachers attempted to capture the variation of fNIRs measurement in prefrontal regions induced by emotional task. If emotional effect could be obtained by fNIRs measurement, a variety of people, such as infants, would be accessible to emotional study. Ozawa *et al.* found stronger increase of the HBO concentration induced by negative pictures than normal pictures. Leon-Carrion *et al.* took advantage of fNIRs measurement to explore emotional effect of different gender in prefrontal cortical region during visual task, and the result showed that the gender affected the functional response in prefrontal cortical region. Angelika *et al.* focused on the sensitivity of the emotional effect in brain by fNIRs measurement, and reported that fear of disgusting sound led to different increase of HBO concentration in the superior temporal gyrus and superior supramargina gyrus. The emotional effect could be effectively measured by fNIRs techniques, however, there is a problem remained, how to select appropriate indicator of the brain functional response provoked by emotional stimuli. The general indicator described by the variation of HBO concentration may be overlaid with other response.

5.6 Distinction between fMRI and fNIRs measurement

In the combination of the fNIRs and fMRI measurement, it provides an opportunity to probe the mechanism of task-related hemodynamic variation in the superficial brain skin. However, the researches described in previous literatures implicitly neglect a principle that the task-related hemodynamic changes of the skin in fNIRs and fMRI are originated from different vascular components, separately. The sensitivity of fNIRs and fMRI depends on the size of the vessel. The fMRI is sensible to skin vessel with the diameter of 1.2 mm to 2 mm[18]. Although the skin vessels of 1.6 mm diameter are responsible for part of the fNIRs signal, fNIRs also reflects the hemodynamic changes in the vessels smaller than 0.7 mm diameter compared to fMRI, due to the maximal light absorption of the vessel. Then, the assumption that fMRI and fNIRs measurement is derived from hemodynamic variation of the same vascular component is acceptable. The fNIRs is suitable to explore the physiological phenomena in small vessels in superficial skin.

5.7 Advantages and defects of fNIRs compared with fMRI

Functional near-infrared spectroscopy and functional magnetic resonance imaging measure the hemodynamic change evoked by tasks or stimuli. The functional brain response could be inferred from the fNIRs. The fNIRs captures information from the change of HBO and HBR, and fMRI gathers the signal from the blood oxygen level dependent signal, obtained from deoxygenated hemoglobin. The fNIRs and fMRI are both originated from hemodynamic change, so it is considerable to infer that fNIRs is correlated with fMRI. Compared with fMRI, the fNIRs has its limitation. First, the spatial resolution of fNIRs is lower than that of fMRI in that the number of measurement signals of fNIRs cannot be equal to that of fMRI. Second, the measurement depth of the cortical activity from fNIRs is smaller than that from fMRI (about 1~3 cm)[32], due to the fact that light only passes several centimeters below the scalp. However, the fNIRs is suitable for many clinic, real life and laboratory applications, because of its low cost, practicability, high ecological validity and high temporal resolution. Besides, fNIRs has the capacity to make use of different types of hemoglobin parameters, such as HBO and HBR, which throws more comprehensive light on the neural process than fMRI, and fNIRs is quiet and comfortable and insensitive to motion[33]. The fNIRs has high temporal resolution, whose sampling rate can be as high as hundreds a second, however the temporal resolution of fMRI is relatively low which reaches about 2~3 s. Then, fNIRs can be sufficient to capture the brain neural response, but fMRI cannot reach it. Likely, fNIRs is effective to measure the faster physiological interference, due to the high temporal resolution, and fMRI fails to record the changes caused by cardiac, respiratory, and other possible fast blood-related variations. The fNIRs is a promising neuro imaging tool for its advantages[34].

6 Conclusion

Significant progress has been made in signal processing technique in fNIRs measurement to eliminate the effect of motion artifact and physiological interference separately. Besides, there are some important issues to be studied, and it is meaningful to gain insight into the mechanism of brain activity during visual, auditory, motor and cognitive stimuli. The brain computer interface and mental workload are the promising fields to be investigated. The emotional effect and the correlation between the deeper neuronal activity and systemic interference are also interesting regions to be studied. According to the literatures, it is foreseeable that fNIRs will be a powerful tool in the future.

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