Review

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From light to insight: Functional near-infrared spectroscopy for unravelling cognitive impairment during task performance

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SUMMARY: Cognitive impairment refers to the impairment of higher brain functions such as perception, thinking or memory that affects the individual's ability to perform daily or social activities. Studies have found that changes in neuronal activity during tasks in patients with cognitive impairment are closely related to changes in cerebral cortical hemodynamics. Functional near-infrared spectroscopy is an indirect method to measure neural activity based on changes in blood oxygen concentration in the cerebral cortex. Due to its strong anti-motion interference, high compatibility, and almost no restriction on participants and environment, it has shown great potential in the research field of cognitive impairment. Recognizing these benefits, this comprehensive review systematically elucidates the rationale, historical development, advantages and disadvantages of functional near-infrared spectroscopy, and also discusses the applications of combining functional near-infrared spectroscopy with other detection techniques. Additionally, this review summarized how functional near-infrared spectroscopy can be applied to cognitive impairment caused by different diseases, ultimately aiding the study of neural mechanisms of cognitive activities, which is crucial for the diagnosis, differentiation and treatment of cognitive impairment.

Keywords: functional near-infrared spectroscopy, cognitive impairment, neurological diseases, psychiatric diseases, rehabilitation of cognitive impairment

1. Introduction

The growing prevalence of cognitive impairment is predominantly attributed to an aging population, further compounded by rising psychological stress. This escalating challenge profoundly undermines individual quality of life and imposes substantial economic strains on families and society. Dementia, a leading cause of cognitive impairment, represents a critical global health challenge, with the number of affected individuals projected to reach 139 million by 2050 (*1*). Another major category of mental disorders associated with cognitive impairment is currently among the most economically burdensome diseases worldwide (*2*).

Cognition encompasses a wide range of intricate and advanced brain functions, such as perception, attention, memory, and thinking. It represents the human brain's capacity to extract, process, and retain information through thought, experience, and emotion. Any factor that disrupts the normal structure and function of the brain can lead to cognitive impairment. Common causes of cognitive impairment include chronic neurodegenerative diseases, stroke, traumatic brain injury (TBI), and mental disorders (*3,4*).

Neurodegenerative diseases affecting memory mainly include Alzheimer's disease (AD), Parkinson's disease (PD) and so on. AD is the leading cause of dementia (*5*). The fifth edition of the Diagnostic and Statistical Manual of Mental Disorders of the American Psychiatric Association (DSM-5) classifies mild cognitive impairment (MCI) and dementia as "neurocognitive disorders", which are prevalent degenerative conditions affecting the central nervous system, primarily in older individuals but also in younger populations, particularly those with genetic predispositions. MCI represents an intermediate stage between normal cognition and dementia, characterized by largely preserved functional ability (*6,7*). Dementia is typically diagnosed when cognitive impairment significantly impairs social or occupational functioning. Mental disorders such as schizophrenia (SCZ), depression, and autism spectrum disorder (ASD), often influenced by genetic factors, are also among the major contributors to cognitive impairment.

However, the diagnosis of cognitive impairment is highly complex. In clinical practice, the diagnosis of

various subtypes of cognitive impairment relies primarily on clinical manifestations and auxiliary examinations. Auxiliary examinations encompass imaging studies, laboratory tests, and other assessments. The clinical manifestations mainly depend on the judgment of the doctor. During cognitive function assessments, clinicians initially conduct a subjective evaluation and closely monitor changes in patients' daily lives. Patients or their family members may report symptoms such as memory loss and cognitive decline. If patients neglect or withhold relevant information, doctors should actively inquire and observe for signs of cognitive decline during communication, such as forgetting important items like keys, appointments, or medication. Patients may also report changes in mood and behavior, including anxiety, depression, or apathy. However, it is crucial to note that a certain degree of cognitive slowing is a typical feature of normal aging (*8*). Distinguishing whether a patient's cognitive decline holds diagnostic significance poses a challenge for general clinicians.

Objective assessment is a crucial component in diagnosing cognitive impairment. Two commonly used screening scales in clinical practice are the Mini-Mental State Examination (MMSE) and the Montreal Cognitive Assessment (MoCA). While these evaluation methods are simple to administer, they can be influenced by subjective factors such as region, language proficiency, and education level of the subjects. Accurate interpretation often requires experienced clinicians. To overcome these limitations, additional auxiliary examinations are frequently employed in the diagnostic process, including functional magnetic resonance imaging (fMRI), electroencephalograms (EEG), and positron emission tomography (PET). But there are still dilemmas in the use of these research tools. EEG has low spatial resolution and poses challenges in source tracing analysis (*9*). The equipment for fMRI is expensive and bulky (*10*), requiring participants to be completely immobilized in a closed and noisy environment during the scanning process which hinders the examination of brain function during task performance (*11*). PET is invasive as it requires the use of radioisotopes and involves ionizing radiation exposure effects (*11,12*). Therefore, the development of new assessment tools for cognitive impairment research is crucial.

Functional near-infrared spectroscopy (fNIRS), is an emerging optical imaging technology that has gained attention in recent years. The myriad advantages it offers in monitoring brain function have piqued the interest of researchers, despite its current nascent stage of development (*13*). fNIRS provides valuable information with high temporal and spatial resolution for localizing brain function during cognitive task performance. This capability enables stereotyping and localization diagnosis of brain function, introducing a new dimension to brain function detection. Furthermore, fNIRS is highly compatible with other techniques, making it a valuable complement to existing detection methods. The integration of multi-dimensional cognitive function evaluation holds the potential to enhance the accuracy and sensitivity of cognitive impairment.

Based on the aforementioned reasons, this review provides a comprehensive summary of the principles, applications, and historical evolution of fNIRS technology. It focuses on the extensive use of fNIRS in the domain of cognitive impairment related to neurological and psychiatric diseases. The objective is to offer a comprehensive overview of the current application status and future prospects of fNIRS in the field of cognitive impairment.

A systematic search of the PubMed database was conducted using the terms "(functional near-infrared spectroscopy OR fNIRS) AND (Cognitive impairment OR Cognitive disorder OR Cognitive decline OR Cognitive dysfunction)", initially identifying 826 articles. To refine the selection, filters were applied for article type, publication period, and language, narrowing the pool to 126 studies. The retrieved records were then imported into a citation management software for further screening and removal of duplicates. Inclusion criteria: Eligible studies encompassed Clinical Studies, Clinical Trials, Comparative Studies, Evaluation Studies, Observational Studies, Randomized Controlled Trials, and Validation Studies. Articles published between 2005 and 2024 were considered, ensuring coverage of nearly two decades of research in the field. Exclusion criteria: Studies were excluded if they were written in non-English languages or if fNIRS was not employed to measure brain activation during cognitive tasks.

2. The rationale for fNIRS

Spectroscopy theory serves as one of fNIRS' fundamental theoretical foundations. The two major chromophores in biological tissues are oxyhemoglobin (HbO_2) and deoxyhemoglobin (HbR). These proteins exhibit different light absorption characteristics for near-infrared light, with absorption varying according to wavelength (Figure 1A). HbR absorbs more strongly below 790 nm, while HbO_2 absorbs more strongly above 790 nm (*14*). During fNIRS measurements, near-infrared light of different wavelengths is emitted by the light source and passes through the layers of cranial structures to reach the neuronal tissue. Within the tissue, light undergoes absorption and scattering. The absorption and scattering processes adhere to the Beer-Lambert law, enabling the noninvasive quantification of cortical HbO_2 and HbR concentrations through a modified Beer-Lambert law (*15*). These concentration changes can be used as surrogate markers of cerebral blood flow (CBF), thus providing a new means to study brain function (*12*).

Another crucial principle underlying fNIRS stems from neurovascular coupling (NC) (Figure 1B). It

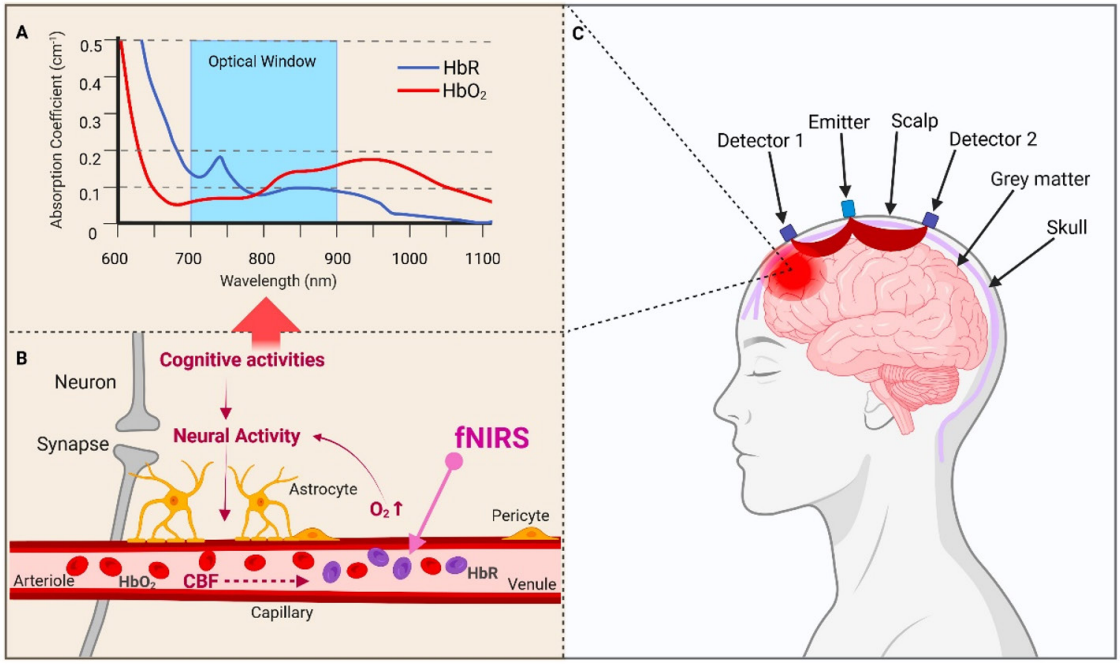

Figure 1. The basic principles of fNIRS. The basic principles of fNIRS including the absorption coefficient of oxygenated and deoxygenated hemoglobin at different wavelengths **(A)**, the mechanism of neurovascular coupling **(B)**, and the propagation path of near-infrared light **(C)**. **(A)**: it shows that oxygenated hemoglobin (HbO_2) and deoxygenated hemoglobin (HbR) can be absorbed simultaneously in the near infrared wavelength range of 700-900 nm. **(B)**: when cognitive activity occurs, cerebral blood flow (CBF) flows from arterioles to venules, local CBF increases, HbR decreases (shown in purple blood cells), HbO_2 increases (shown in red blood cells), and more O_2 is produced to supply neuronal activity. Thus, fNIRS can indirectly reflect the neuronal activity by measuring the changes of HbO_2 and HbR. **(C)**: illustration of the path (shown in red banana shape) followed by the near-infrared photons from the light source through the different layers of the head to the detector.

involves the intricate connections between neural activity, CBF, and blood oxygen levels. These connections involve neurons, glial cells, neurotransmitters, and chemical molecules within the brain microenvironment. Increased neuronal activity leads to an elevation in regional CBF, meeting the higher metabolic demands of the brain while simultaneously triggering an increase in oxygen delivery (*16*). Furthermore, NC involves a process wherein heightened brain activity during affective or cognitive tasks corresponds with increased blood flow and oxygen consumption (*17*). Neuronal activity relies on oxygen supplied through blood metabolism to sustain its functionality. Consequently, local changes in cerebral hemodynamics occur during cognitive processes, leading to enhanced blood flow towards activated brain regions, which is reflected by an increase in HbO_2 concentration and a decrease in HbR concentration (*15*).

Based on the aforementioned theory, fNIRS is a non-invasive and safe technique that utilizes near-infrared light to target specific brain regions on the surface of the subject's head. This light, with a wavelength range of 700-900 nm, can penetrate the skull and reach the cerebral cortex, which is approximately 20-30 mm deep in the brain, after undergoing reflection, scattering, and absorption by the tissue. The emitted light then exits the scalp in a "banana-shaped" path and is captured by a nearby detector (Figure 1C) (*11*). fNIRS enables the assessment of relative concentration variations of two hemoglobin species within the cerebral cortex through the detection of light absorption at distinct wavelengths. This approach provides insights into CBF alterations, facilitating the monitoring of local brain tissue metabolism. Consequently, it allows for an understanding of neural activity in the brain during cognitive tasks.

3. History of fNIRS development and application in the field of cognition

The development and application of fNIRS in the field of cognition can be traced back to the late 1970s when Jobsis first reported the use of near-infrared light to noninvasively monitor changes in cortical tissue oxygenation in cats (*18*). In 1993, Hoshi and colleagues used fNIRS to study cognitive function and found that HbO_2 concentration increased and HbR concentration decreased in the prefrontal cortex (PFC) of subjects during task performance (*19*). And they first recorded PET and fNIRS data simultaneously in 1994 (*20*).

The ability of fNIRS to monitor oxygenation levels led to its rapid application in various diseases, including mental disorders (*21*), stroke (*22*), PD (*23*), multiple sclerosis (MS) (*24*), and so on. In 1996, Kleinschmidt performed the first simultaneous fMRI and fNIRS to record human brain activation (*25*). In 1997, Fallgatter published the first article in his series of fNIRS studies, demonstrating a loss of hemispheric functional asymmetry in Alzheimer's

dementia (*26*). In 1998, the first commercial single-channel continuous wave imaging system was used in neonates, and an increase in HbO_2 was found in the visual cortex of awake infants induced by visual stimuli (*27*). Sakatani *et al*. used fNIRS to measure changes in HbO_2 and HbR in the frontal lobes of Parkinson's patients during electrical stimulation. They found that these changes resembled those observed during cognitive tasks, indicating the involvement of a complex neuronal circuit in the frontal lobe (*23*). In 2004, Macket *et al*. recorded the first simultaneous magnetoencephalogram (MEG) and fNIRS data (*28*). fNIRS has been increasingly utilized to investigate a wide range of cognitive domains, including executive function, attention, memory, language, cognition, and decision-making. Numerous studies have employed fNIRS to elucidate the neural mechanisms underlying infant brain development and cognitive maturation (*29-31*). With its high ecological validity, fNIRS enables the observation of brain activity during naturalistic settings and realistic social interactions. Moreover, fNIRS has been applied to studying cognitive processes in diverse real-world scenarios (*32,33*). Looking ahead, this technique holds promise for applications in everyday life, providing insights into the brain activity patterns of healthy adults during dynamic, real-world tasks and contributing to a deeper understanding of human behavior.

With the deepening of research, the equipment for fNIRS is being gradually upgraded. In 1989, the first commercial single-channel fNIRS system was introduced (*34*). In 1998, the first 10-channel fNIRS system was first used in the clinic (*35*). Initially, before 2010, the focus was primarily on increasing the number of channels, transitioning from single-channel or multiple measurements to multi-channel systems for a single measurement. Presently, more advanced high-density systems have been developed to accurately measure the blood flow in the cerebral cortex over a wider range. To enhance the applicability of fNIRS in various experimental environments and fields, efforts have been made to free the equipment from complex fiber optic cables. In 2009, a battery-powered wireless 22-channel system for adult PFC measurement appeared (*36*). Nowadays, multi-channel, wireless portable wearable devices have been used in many fNIRS studies, and fNIRS has made important progress in understanding brain activity, which is one of the potential advantages of fNIRS over other neuroimaging modalities. Advancements in hardware have led to the development of new high-density fNIRS systems, enabling comprehensive whole-brain measurements. Future efforts in fNIRS design are likely to focus on further enhancing the temporal and spatial resolution of the technology, as well as improving its overall accuracy. (Figure 2).

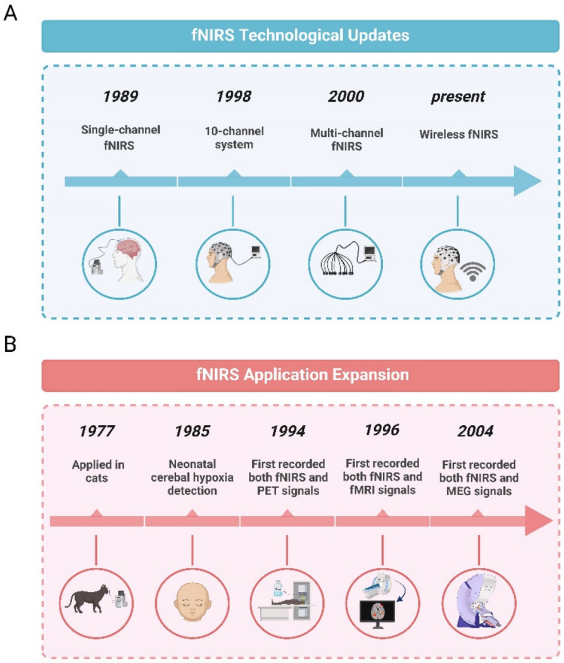

Figure 2. The historical development of fNIRS. Illustration of technology updates **(A)** and application expansion **(B)** of fNIRS at different points in time.

4. Application of fNIRS in the cognitive domain

In recent years, brain cognitive function has remained a focal point of research in neuroimaging and electrophysiology. The diagnosis of cognitive impairment necessitates a combination of subjective assessment and objective evidence. Commonly utilized imaging modalities in clinical practice include fMRI, EEG, and PET. Meanwhile, fNIRS has undergone significant advancements, evolving from single-channel to multi-channel systems and from single-region to whole-brain imaging. This progress has overcome previous limitations in studying brain regions associated with cognitive function, paving the way for broader clinical applications. fNIRS offers several advantages over other imaging techniques when applied in the cognitive domain.

Firstly, fNIRS is currently the only hemodynamic neuroimaging technology capable of directly monitoring changes in the concentration of both HbO_2 and HbR (*37*). In contrast, the blood oxygen level dependent (BOLD) responses measured by fMRI are based on the proportion of HbR and do not provide information on hemoglobin concentration alone (*14*). The richer information provided by fNIRS allows for a more intuitive reflection of cortical activity and facilitates the use of differential analysis techniques, making it well-suited for real-time monitoring of temporal and spatial changes in cerebral blood oxygenation during cognitive tasks. Some researchers have even suggested that HbO_2 may be a more reliable indicator of cortical activation than HbR (*38*).

Secondly, fNIRS is able to detect changes in the cerebral hemodynamics of participants during task

execution and is applicable to all possible participant populations, from newborns to the elderly, with fewer restrictions on participant behavior. Additionally, fNIRS is portable and easy to wear, allowing for studies involving freely moving subjects without being constrained by the experimental environment. This makes fNIRS particularly suitable for research on cognitive tasks performed in naturalistic settings by individuals of different age groups (*39*).

Thirdly, compared with EEG, fNIRS offers a higher spatial resolution, which can locate the brain response to specific cortical areas (*12*). Compared with fMRI, fNIRS provides a higher temporal resolution, enabling better differentiation of signal contamination caused by physiological system signals and motion artifacts. Moreover, fNIRS is a non-ionizing technique, making it safer for human use compared to PET (*9*).

Finally, fNIRS demonstrates compatibility with other electrical and magnetic devices (*40*). fNIRS can be used simultaneously with fMRI, EEG, PET (*41*) to complement each other achieve optimized imaging analysis. Studies have reported that combining fNIRS with another neuroimaging technique, such as EEG or fMRI, yields more efficient detection results than using either method alone (*42*). Additionally, fNIRS can be used to further investigate the mechanisms of neural stimulation techniques, including transcranial direct current stimulation (*43*). Apart from these unique advantages, fNIRS also possesses universal benefits such as non-invasiveness, cost-effectiveness, portability, and noise-free operation. Table 1 provides a comparison between fNIRS and commonly used imaging examinations in the cognitive field (*15,44,45*).

5. Combined application of fNIRS and other imaging techniques in the cognitive domain

At present, numerous studies highlight the potential benefits of integrating fNIRS and other imaging techniques, allowing researchers to investigate brain function from multiple perspectives and obtain a more comprehensive understanding of neural processes.

The combination of EEG and fNIRS offers advantages in terms of temporal and spatial resolution. EEG provides high temporal resolution, capturing the fast dynamics of neuronal electrical activity, while fNIRS provides better spatial resolution, allowing for the localization of cortical activation. Moreover, EEG and fNIRS measure different aspects of brain activity, with EEG reflecting neuronal electrical activity and fNIRS capturing metabolic responses. This built-in validation of identified brain activity enhances the reliability of the results obtained from these two modalities (*46*). The complementary nature of the measurements obtained from EEG and fNIRS can provide a more comprehensive understanding of brain activity and function, offering a unique neural monitoring platform to investigate the NC mechanism (*47*).

A study conducted by Cicalese *et al*. (*48*) examined the classification of subjects based on the degree of dementia using an EEG-fNIRS hybrid model. The results showed that when EEG and fNIRS were used

Table 1. The comparison of fNIRS with other neuroimaging techniques

Technology	Advantages	Disadvantages	Indications	Contraindications
fNIRS	1.Good temporal resolution 2.Good spatial resolution 3.Insensitive to motion artifacts 4.Good compatibility 5.Non-invasive 6.Portable and cost-effective	1.Restricted to cortical measurements	1.Safe for all age groups 2.Cognitive and behavioral studies 3.Real-time brain monitoring	1.Care with severe scalp injuries
fMRI	1.Excellent spatial resolution 2.Whole-brain imaging 3.Non-invasive	1.Limited temporal resolution 2.Sensitive to movement artifacts 3.Expensive and non-portable 4.Limited compatibility 5.Relatively noisy	1.Functional brain mapping 2.Neurovascular coupling studies	1.Claustrophobia 2.Metal implants or devices 3.Severe kidney dysfunction (due to contrast agents)
EEG	1.Excellent temporal resolution 2.Non-invasive 3.Portable and cost-effective	1.Limited spatial resolution 2.Prone to noise from muscle activity 3.Limited compatibility 4.Requires conductive scalp gel	1.Rapid detection of brain activity	1.Severe scalp injuries 2.Hypersensitivity to conductive gel
PET	1.Good spatial resolution 2.High sensitivity for metabolic activity 3.Target specific molecules with tracers	1.Limited temporal resolution 2.Invasive 3.Limited compatibility 4.Expensive and non-portable	1.Metabolic brain function studies	1.Pregnancy and children 2.Severe kidney dysfunction 3.Allergies to radiotracers

Abbreviation: fNIRS: functional near-infrared spectroscopy. fMRI: functional magnetic resonance imaging. EEG: electroencephalograms. PET: positron emission tomography.

independently, the accuracy was 65.52% and 58.62%, respectively. However, when the EEG-fNIRS hybrid model was employed, the accuracy increased to 79.31%, demonstrating the enhanced performance achieved by integrating the complementary characteristics of EEG and fNIRS. These findings suggest that the hybrid EEG-fNIRS system holds promise as a tool to enhance the diagnostic and evaluation processes for diseases such as AD. Cognitive deficits in AD have been linked to the disruption of brain networks (*49*). Li (*50*) used the fNIRS-EEG method to investigate the dynamic and local changes in AD-related brain networks, demonstrating the feasibility of this technique. This approach allows for the examination of both hemodynamic and electrical aspects of brain activity, providing valuable insights into the pathophysiology of AD.

The combination of fMRI and fNIRS is one of the most commonly used multimodal imaging approaches. This is because fMRI equipment is generally not suitable for conducting experiments with participants in sitting or standing positions (*51*). On the other hand, fNIRS is applicable to a wide range of experimental conditions and can accommodate participants in various positions. Additionally, while fNIRS provides limited whole-brain coverage, the high spatial resolution of fMRI compensates for this limitation, resulting in a complementary combination of the two techniques.

Some researchers have used fMRI and fNIRS to verify the feasibility of combining multiple techniques. Pereira (*52*) employed the fMRI-fNIRS multimodal approach to examine the possibility of converting spatial neuronal information from fMRI motion patterns into fNIRS settings of HbO_2 and HbR concentrations. This innovative technique aimed to enhance the understanding of motor function by revealing detailed information about neural activity using fNIRS measurements.

6. Application of fNIRS in the cognitive impairment related to neurological and psychiatric diseases

6.1. Cognitive impairment associated with neurological diseases

6.1.1. Alzheimer's disease

AD is the most prevalent neurodegenerative disease globally and currently lacks a cure. Early pharmacological intervention and regular physical exercise can decelerate disease progression and enhance patients' quality of life (*53*). MCI acts as a transitional stage between normal aging and AD. It is important to note that not all individuals with MCI will progress to AD (*54*). MCI can serve as an early indicator of AD, and early diagnosis is crucial for timely intervention to delay the onset of dementia (*55*).

fNIRS has shown promise in this area and provided insights into the functional alterations in the brain section associated with cognitive impairment. Ates suggests that the neural network behind emotion enhanced memory may involve interactions between frontal and subcortical regions. So, Ates and his colleagues used fNIRS to measure cortical activity during an emotional n-back task in 20 AD patients and 20 healthy older adults of similar age and sex. They found that only in positive emotional words, AD patients have higher HbO_2 concentrations than healthy controls, and the cortical activity of AD patients with positive emotion words was hemispheric and left side activity was higher (*56*). Katzorke *et al*. selected 110 subjects from a cohort of 604 participants, half each with MCI patients and half each with healthy controls. Using fNIRS to measure hemodynamic responses during a verbal fluency task (VFT), the investigators found decreased hemodynamic responses in the inferior frontotemporal cortex in the MCI group. The hemodynamic response pattern during VFT can be used as one of the bases for early detection of AD (*57*). These studies show that AD or MCI patients with cognitive decline have reduced cortical oxygenation during cognitive tasks, which is consistent with the previous argument (Figure 3).

Studies have shown that visuospatial deficits are one of the first symptoms of AD and are associated with lower activation of the parietal epithelial cortex as assessed by functional imaging (*58*). Zeller *et al*. (*59*) utilized fNIRS to investigate the activation of parietal regions in patients with AD and healthy subjects during visuospatial tasks. Interestingly, they found that although healthy subjects exhibited significant parietal activation, there was no difference in visuospatial performance between the two groups. In a study by Haberstumpf *et al* long-term participation in the Vogel Study was analyzed in healthy older adults performing a clock-hand-angle discrimination task (ADT) during visuospatial processing. Using fNIRS, significant activation in the parietal cortex was observed during visuospatial tasks, and this activation showed a significant increase in neuronal brain activity with increasing task difficulty (*60*). Building upon these findings, Haberstumpf *et al*. conducted a similar study on individuals with MCI (*61*) the activation of the parietal cortex, observed in healthy subjects, was significantly reduced in MCI patients. These results suggest that deficits in visuospatial processing in the parietal cortex may serve as a risk factor for the progression of MCI or AD. Therefore, measuring parietal cortex activation using fNIRS could potentially be employed as a reliable marker for the early detection and diagnosis of AD.

Cognitive function requires a high level of functional interaction between network region. Functional connectivity, which refers to the synchronized activity between different brain regions, is thought to play a crucial role in cognitive processes. Research suggests that changes in functional connectivity may precede alterations in the activation of specific brain regions

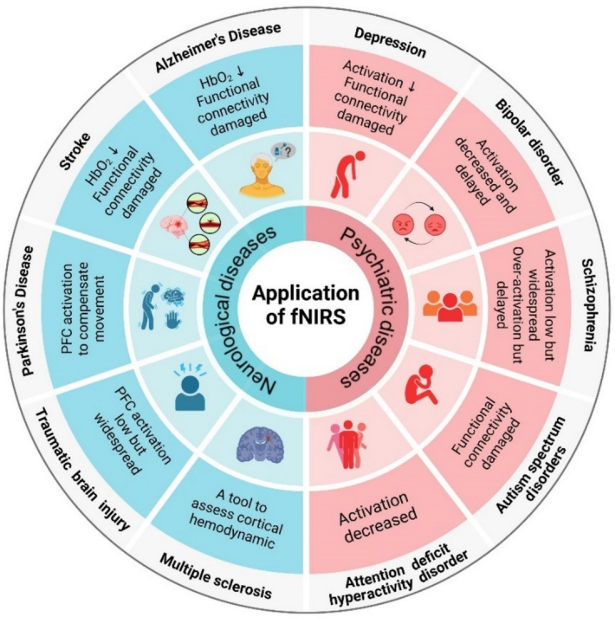

Figure 3. Application of fNIRS in cognitive impairment associated with central nervous system diseases. Illustration of application of fNIRS in the cognitive impairment related to neurological and psychiatric diseases. Left: neurological diseases (shown in blue), including Alzheimer's disease (AD), stroke, Parkinson's disease (PD), traumatic brain injury (TBI) and multiple sclerosis (MS). Using fNIRS, decreased HbO_2 and impaired brain functional connectivity can be detected in some regions of the cerebral cortex in AD and stroke patients, activation of the non-motor prefrontal cortex (PFC) can be observed in PD patients to compensate for motor function, and lower but more extensive activation of the PFC can be detected in TBI patients. In patients with MS, fNIRS can be used as a tool to assess cortical hemodynamics. Right: psychiatric diseases (shown in pink), including depression, bipolar disorder (BD), schizophrenia (SCZ), autism spectrum disorders (ASD) and attention deficit hyperactivity disorder (ADHD). Using fNIRS, decreased cortical activation and impaired brain functional connectivity can be detected in patients with depression, decreased and delayed cortical activation can be observed in BD patients, reduced but more widespread cortical activation in SCZ patients, or delayed over-activation, can be detected, damaged brain functional connectivity can be observed in ASD patients, and decreased cortical activation can be detected in ADHD patients.

(*62*). Tang and Chan (*54*) used fNIRS to analyze the functional connectivity of mild AD, MCI, and normal aging and found that the brain network of normal aging individuals exhibited higher regularity compared to AD patients, indicating that fNIRS can be a feasible tool for distinguishing AD from normal aging based on functional connectivity patterns. Nguyen *et al*. (*63*) used fNIRS to detect brain functional connectivity in cognitively normal older adults and patients with MCI, and found that in the VFT task, the inter-hemispheric connectivity in the healthy control group was significantly higher than the intra-hemispheric connectivity. It can be used as an effective indicator to distinguish cognitively normal elderly from MCI patients. In addition, left hemisphere connectivity was significantly reduced in MCI patients during the VFT task, and these findings demonstrate the potential of fNIRS to study brain functional connectivity in neurodegenerative diseases. Chan *et al*. (*64*) also proposed that brain functional connectivity analysis based on fNIRS can be used as an effective set of features for the diagnosis of AD, and AD patients have loss of brain functional connectivity and non-significant laterality. Moreover, connectivity disruption and frontal lobe oxygenation changes are more severe in AD patients than in patients with mild cognitive impairment (Figure 3) (*11*).

6.1.2. Stroke

Cognitive impairment is a common consequence of stroke, and fNIRS has emerged as a valuable tool for assessing brain activity and monitoring changes during cognitive tasks in patients with post-stroke cognitive impairment (PSCI) (*65,66*). Kong *et al*. (*65*) specifically focused on evaluating the functional connectivity of relevant cortex during memory tasks using fNIRS. They found that a decreased level of functional connectivity may serve as a marker of PSCI (Figure 3). Zou *et al*. employed fNIRS to study the differences in functional connectivity of brain networks between patients with PSCI and healthy controls. They discovered that the functional connectivity of brain networks in PSCI patients was significantly lower compared to healthy controls. However, there was no significant difference in functional connectivity between PSCI patients and stroke patients without PSCI (*67*).

fNIRS is frequently used to assess the effectiveness of cognitive rehabilitation in stroke patients. Monitoring changes in brain activity during rehabilitation training using fNIRS is crucial for understanding the compensatory changes that underlie functional recovery after brain injury, ultimately improving the outcomes of rehabilitation interventions (*68*). Yang *et al*. (*69*) used fNIRS to evaluate the effect of transcranial direct current stimulation (tDCS) on the rehabilitation of cognitive impairment in stroke patients. After tDCS treatment, fNIRS measured increased activation of the left superior temporal cortex and improved functional connectivity between the cerebral hemispheres in stroke patients. Huo *et al*. (*70*) used fNIRS to evaluate the changes in effective connectivity within the cortical network induced by median nerve electrical stimulation (MNES) in stroke patients, and found that the effective connectivity between bilateral prefrontal PFC and left occipital lobe (LOL) in stroke patients in the MNES state was significantly higher than that in the resting state. Zhang *et al*. (*71*) used fNIRS as one of the indicators to evaluate the effect of intermittent theta burst stimulation (iTBS) combined with cognitive training on the treatment of PSCI. The left dorsolateral prefrontal cortex (DLPFC), prefrontal polar cortex, and left Broca's region were activated. These studies collectively suggest that fNIRS can serve as an effective tool for monitoring and evaluating brain activity in stroke patients undergoing cognitive rehabilitation. By providing objective measures of brain function, fNIRS can assist clinicians in

formulating and optimizing individualized rehabilitation treatment programs, as well as accurately assessing rehabilitation efficacy and prognosis.

6.1.3. Parkinson's Disease

PD is a neurodegenerative disorder characterized by motor symptoms and various non-motor symptoms, including cognitive decline, particularly in executive function (*72*). Stuart *et al*. used fNIRS to measure PFC activity during tasks to distinguish between PD patients and healthy individuals (*73*). It has been shown that executive dysfunction leads to freezing of gait (FOG), which is a common episodic disorder in PD patients (*74*). Previous studies have shown that PD patients often compensate for impaired motor function by activating the PFC (*75*). Currently, in PD, fNIRS is mainly used to investigate changes in cortical activity during gait and postural stability tasks (*76*). Maidan *et al*. (*77*) used fNIRS to measure HbO_2 levels in Brodmann area 10 before and during FOG revealing a direct association between FOG and dysfunction in the frontal lobe. However, there are exceptions to the compensatory activation pattern. Bonilauri *et al*. (*78*) used fNIRS to evaluate PD at different stages. They divided 39 PD patients into early PD and middle PD groups based on the Hoehn-Yahr (HY) scale and employed a whole-head fNIRS system with 102 measurement channels to monitor brain activity. The group-level activation map indicated that the middle PD group exhibited higher activation in the frontal regions compared to the early PD group, while the opposite pattern was observed in the motor and occipital regions. This suggests that the PFC in non-motor regions may provide a compensatory mechanism for PD-related movement disorders (Figure 3).

6.1.4. Traumatic brain injury

TBI can result in long-term neurobehavioral and cognitive impairment (*79*). Executive function deficits, which involve the PFC, are commonly observed in patients with neurocognitive impairment following TBI (*80*). Chang *et al*. recruited 37 patients with neurocognitive impairment after TBI and 60 healthy controls to measure HbO_2 in the PFC region during the Stroop and n-back tasks using a 22-channel fNIRS device. The results revealed that TBI patients exhibited lower but more widespread brain activation during the 2-back and Stroop color word congruency tasks compared to healthy controls (Figure 3) (*81*). Plenger *et al*. used fNIRS to evaluate neural changes in TBI patients during the Stroop task. Compared with the healthy group, the patient group had a significant increase in HbO_2 in the bilateral frontal lobe and greater neural activity in the frontal lobe (*82*). These findings indicate the potential of fNIRS in identifying frontal inefficiency in TBI patients.

6.1.5. Multiple sclerosis

MS is a degenerative disease that affects the central nervous system, characterized by inflammation, demyelination, and axonal damage (*83*), and cognitive impairment and motor impairment are common in patients with MS (*84*). Stojanovic-Radic *et al*. (*85*) used fNIRS to examine differences in neural activation in the orbitofrontal brain regions during a working memory (WM) task between individuals with MS and healthy controls. The results demonstrated that the MS group exhibited elevated HbO_2 concentrations and increased brain activation in the left superior frontal gyrus at lower levels of task difficulty (1-back), but decreased activation at higher levels of task difficulty (2-back and 3-back) compared to healthy controls (Figure 3). This study was the first to utilize fNIRS to investigate brain activation during a cognitive task in individuals with MS.

The application of fNIRS in cognitive impairment in neurological diseases are reported in Table 2.

6.2. Cognitive impairment associated with Psychiatric diseases

Cognitive impairment is a common characteristic of various mental disorders, including depression. fNIRS has emerged as a valuable tool in psychiatric research, allowing for the measurement of cortical dysfunction during cognitive tasks. It has been utilized in several mental disorders such as SCZ, Major depressive disorder (MDD), and bipolar disorder (BD) The application of fNIRS in cognitive impairment in psychiatric diseases are summarized in Table 3.

6.2.1. Depression

Depression is often associated with cognitive impairment (*86*), and executive function, which relies on the PFC, is one aspect of cognition that is affected. The PFC is involved in various high-level cognitive functions, including executive function, WM, and language processing (*87*).

Kondo *et al*. (*88*) used fNIRS to assess changes in prefrontal and temporal lobe HbO_2 concentrations during pleasant and unpleasant image recall tasks in patients with MDD and healthy controls. It was found that HbO_2 in the bilateral frontal region of MDD group was significantly lower than that of the control group during the unpleasant state. Downey *et al*. (*89*) used fNIRS to measure frontal lobe hemodynamic responses during category VFT and WM n-back tasks in depressed patients and found that bilateral frontal lobe hemoglobin responses were lower. Liu (*90*) used fNIRS to monitor the concentration of HbO_2 in the brain of adolescents with depression and healthy controls. The study revealed that depressed adolescents exhibited significantly lower cortical activation of hemodynamic responses in the PFC

compared to healthy controls. The mean inter-channel connectivity strength was also found to be higher in the healthy control group than in the depression group. These findings suggest that adolescents with depression exhibit abnormal brain activation patterns and reduced task-related functional connectivity compared to their healthy counterparts. In Ishii's study, MDD patients showed significantly lower activation in PFC areas and inferior parietal areas, especially in the left, when performing a word-making task than controls (*91*). These studies suggest that the brains of depressed patients exhibit abnormal activation patterns compared to healthy controls, and fNIRS may be a useful tool for assessing psychophysiological indicators of depressed patients and distinguishing depressed patients from normal individuals (Figure 3).

6.2.2. Bipolar disorder

BD, characterized by the presence of both manic and depressive episodes, with depressive episodes being a typical symptom. Similar to depression, the PFC plays a significant role in the pathophysiology of BD. Kameyama (*92*) used fNIRS to compare changes in HbO_2 concentration in the frontal lobe during cognitive and motor tasks in BD, MDD, and healthy controls. The study found that individuals with BD exhibited delayed onset activation in the frontal lobe (Figure 3), while those with MDD showed reduced activation in the frontal lobe. These differences in frontal activation patterns suggest that fNIRS may be a reliable tool for differentiating between BD and MDD. Nishimura (*93*) compared prefrontal hemodynamic responses during cognitive tasks between the hypomanic and depressive states in individuals with BD. They used fNIRS to assess prefrontal function during VFT in hypomanic, depressed, and healthy control groups. The study revealed that VFT performance did not differ significantly between the hypomanic, depressive, and healthy control groups. However, the activation rate in the PFC was significantly lower in individuals with BD compared to the healthy control group (Figure 3). The left DLPFC exhibits significantly greater hemodynamic changes in individuals with BD during hypomanic episodes compared to those with depression. Furthermore, the severity of hypomanic symptoms was positively correlated with activation in the left DLPFC and frontopolar cortex in BD patients. Follow-up measurements in hypomanic patients showed decreased prefrontal activation after the resolution of hypomanic symptoms. These findings suggest that there are distinct differences in prefrontal hemodynamics corresponding to manic and depressive states in individuals with BD, and fNIRS may serve as a valuable tool for objectively assessing the state-dependent characteristics of prefrontal hemodynamics in BD.

6.2.3. Schizophrenia

Cognitive impairment is a core feature of SCZ and is often observed years before the onset of overt psychotic symptoms (*94*). Koike (*95*) used multi-channel fNIRS to measure hemodynamic changes during n-back WM tasks with different cognitive loads in patients with SCZ and healthy controls and found that the activation of prefrontal activity was reduced but more extensive in SCZ patients (Figure 3). Noda (*96*) used fNIRS to focus on the changes in HbO_2 levels in the prefrontal and temporal lobes in the late stage of the task and found an abnormal re-increase of HbO_2 levels. Kumar (*97*) used fNIRS to examine hemodynamic activity during WM tasks in SCZ. The results found delayed but compensatory hyperactivation in the right frontopolar cortex of the SCZ (Figure 3), which, the authors speculate, may underlie the WM deficit in the SCZ. According to the above studies, Hemodynamic changes in WM of patients with chronic SCZ detected using fNIRS may be a potential biomarker.

As a novel neurophysiological approach, fNIRS is increasingly being used in the study of SCZ and frontal lobe dysfunction. To date, several studies have employed fNIRS to assess hemodynamic changes in the frontal lobe in various contexts, demonstrating that distinct hemodynamic response patterns may serve as potential imaging biomarkers in individuals with SCZ and fNIRS may become an effective clinical tool for evaluating this population.

6.2.4. Autism spectrum disorder/ attention deficit hyperactivity disorder

ASD is characterized by impaired social communication accompanied by stereotyped behaviors and limited interests (DSM-5). Executive dysfunction is partly responsible for these symptoms (*98*). A special feature of fNIRS for this population is the ability to study neural development from an early age (*99*), leading to a better understanding of the neural mechanisms of ASD. Unlike fMRI, which requires a closed environment with loud noise and patient immobilization, fNIRS is quiet and portable, making it more suitable for individuals with ASD who may have difficulty tolerating the fMRI environment (*100*). However, some individuals with ASD may also resist wearing near-infrared caps, limiting the feasibility of traditional fNIRS approaches (*101*), Therefore, the development of remote and non-contact near-infrared systems is a future direction in this field. Chan *et al*. (*102*) used fNIRS to measure prefrontal hemodynamic data in individuals with ASD and typically developing (TD) individuals. The study revealed significantly lower functional connectivity in the PFC of individuals with ASD compared to TD individuals. Han *et al*. (*103*) used fNIRS to investigate the impact of WM load on functional connectivity in the PFC of individuals with ASD. The findings revealed that individuals with high-functioning ASD exhibited WM impairment that was accompanied by load-dependent changes in intra-

Table 2. Summary of fNIRS applications on neurological diseases

Reference	Research object	Activation Task	Brain Region	Results	Evidence
Zeller (*59*)	Mild **AD**: *n* = 13 HC: *n* = 13	Modified version of the BLOT (line orientation versus color naming)	Parietal	AD especially low increases in [oxy-Hb] during line orientation were found in the upper half of the probe set covering the superior-parietal cortex.	AD showed significantly less increase in [oxy-Hb] in the superior-parietal cortex in the line orientation task than controls, but there was no difference in color naming.
Ateş (*56*)	**AD**: *n* = 20 HC: *n* = 20	The n-back task (0-back, and 1-back WM task)	Bilateral prefrontal	In the PEW condition, activity in Ch8 and Ch11 (left ventral PFC) was significantly higher in the AD compared to HC after FDR correction.	AD had the higher [oxy-Hb] than the HC only in the PEW condition.
Katzorke (*57*)	**MCI**: *n* = 55 HC: *n* = 55	The letter VFT; the category VFT	Bilateral frontotemporal	Both hemispheres of MCI showed decreased hemodynamic responses in the inferior frontotemporal region in category VFT compared to HC (HC: −2.53 ± 0.39; MCI: −1.08 ± 0.39).	MCI had a decreased hemodynamic response in the inferior frontotemporal cortex.
Tang & Chan (*54*)	Mild **AD**: *n* = 18 **MCI**: *n* = 12 HC: *n* = 31	The category VFT	Prefrontal	FC edge count decreased across groups (T2a: HC=307, MCI=193, AD=170; T2b: HC=49, MCI=30, AD=25). In AD, FC distribution became evenly spread across the left and right PFC.	AD had loss of FC and insignificant laterality between left and right PFC.
Nguyen (*63*)	**MCI**: *n* = 42 HC: *n* = 42	4 different paradigms: a resting state, an oddball task, a 1-back task and a VFT	Prefrontal	During VFT, MCI inter1-4 hemispheric connectivity ([oxy-Hb]) was significantly lower than HC (p = 0.002, 0.003, 6E−5, 7E−4).	MCI reduced significantly left hemisphere connectivity on the VFT.
Y. L. Chan (*64*)	Mild **AD**: *n* = 16 HC: *n* = 26	The category VFT	Prefrontal	Mild AD showed significantly lower connectivity than HC using the proposed method ($p < 0.05$), with no significant laterality detected ($p > 0.05$).	AD had loss of connectivity and insignificant laterality.
Haberstumpf (*61*)	**MCI**: *n* = 59 HC: *n* = 59	The clock-hand-angle discrimination task	Parietal	MCI showed reduced brain activity in the ROI compared to HC (MCI: Mean = 0.03, SD = 0.04; HC: Mean = 0.05, SD = 0.05).	MCI showed significantly less increase in cortical activation and reduced brain activity and laterality compared to HC.
Huo (*70*)	**Stroke**: *n* = 23	The resting state; the MNES state	Bilateral PFC, motor cortex, and occipital lobe	Effective connectivity increased significantly (left PFC→LOL: P = 0.048; right PFC→LOL: P = 0.002).	Stroke in the MNES state had significantly higher effective connectivity from left PFC and right PFC to LOL compared with the resting state.
C. Yang (*69*)	**Stroke**: *n* = 22 HC: *n* = 14	The letter VFT	Prefrontal	Stroke had lower β values than HC. FC between bilateral hemispheres in stroke increased after 14 tDCS sessions, notably between the 7th and 14th sessions.	The FC between the cerebral hemispheres and the cortical activation of stroke patients was lower than that of HC but increased after tDCS.

Abbreviation: AD: Alzheimer's disease. HC: healthy control. BLOT: Benton Line Orientation Task. [oxy-Hb]: oxygenated hemoglobin. WM: working memory. PEW: positive emotional words. FDR: false discovery rate. MCI: mild cognitive impairment. VFT: verbal fluency task. FC: functional connectivity. PFC: prefrontal cortex. ROI: region of interest. SD: standard deviation. MNES: Mini-Mental State Examination. LOL: left occipital lobe. tDCS: transcranial Direct Current Stimulation. PSCI: Post-stroke cognitive impairment. STR: patients without cognitive impairment after stroke. CDT: Clock drawing test. DST: Digit span test. CBT: Corsi Block-tapping test. RHD: patients with PSCI who have right hemisphere damage. CPT: continuous performance test. NPSCI: Non-PSCI. YA: young adults. OA: older adults. PD: Parkinson's Disease. CSRT: choice stepping reaction time task. iCSRT: inhibitory choice stepping reaction time. SST: a Stroop stepping test. SMA: supplementary motor areas. MD: mean difference. CI: confidence interval. TBI: traumatic brain injury. DLPFC: dorsolateral prefrontal cortex. VLPFC: ventrolateral prefrontal cortex. MS: multiple sclerosis.

Table 2. Summary of fNIRS applications on neurological diseases (continued)

Reference	Research object	Activation Task	Brain Region	Results	Evidence
Kong (*65*)	PSCI **(Stroke)**: *n* = 19 STR: *n* = 27 HC: *n* = 26	The CDT, DST, and CBT	Bilateral motor sense cortex and prefrontal lobe	FC between motor sense and frontal lobe was the lowest in PSCI ($P < 0.05$).	PSCI showed decreased FC between bilateral motor sense cortex and between motor sense cortex and frontal lobe during CDT and CBT.
X. Li (*66*)	RHD **(Stroke)**: *n* = 16 HC: *n* = 32	The X version of CPT	Prefrontal	No significant [Oxy-Hb] activation in HC after ~35 s, while RHD showed multiple reactivations in bilateral PFCs with greater activation than HC, exceeding the first peak.	RHD had neural compensation in both prefrontal lobes; but the rate of compensation was slower on the affected side.
Zou (*67*)	PSCI **(Stroke)**: *n* = 16 NPSCI: *n* = 16 HC: *n* = 16	The resting-state	Prefrontal, somatosensory, and motor cortices	Interhemispheric FC: $p = 0.005$, $p = 0.013$, Bonferroni corrected. Right hemisphere FC: $p = 0.008$, Bonferroni corrected.	PSCI exhibited significantly decreased interhemispheric FC and intra-right hemispheric FC compared with the HC.
Stuart (*73*)	**PD**: *n* = 24 YA: *n* = 25 OA: *n* = 19	2 different motor tasks: a 2-min 360◦ turning-in-place task, a 2-min walking task	Prefrontal	Significant differences during walking: overall PFC ($p = 0.025$), left PFC ($p = 0.012$), and early walking period (first 40s, $p = 0.007$).	PD had higher PFC activation than YA and OA during walking and turning, with significant group differences for bilateral PFC activation, left PFC activation, and the early period (first 40s) of walking.
Sharon (*75*)	**PD**: *n* = 34 OA: *n* = 26	Obstacle negotiation task	Prefrontal	PD exhibited a greater increase in PFC activation than OA across phases (interaction: group x PFC activation, $p < 0.001$, Cohen's d = 0.63).	PD showed greater increases in PFC activation during and after obstacle crossing compared to the OA.
Pelicioni (*76*)	**PD**: *n* = 52 HC: *n* = 95	Three stepping tests (CSRT, iCSRT, and SST)	Dorsolateral PFC, Broca's area, SMA, and premotor cortex	DLPFC: [MD: −2.44, 95% CI: −4.32 to −0.55], $p = 0.012$; SMA: [MD: −2.25, 95% CI: −4.35 to −0.16], $p = 0.035$; Premotor cortex: [MD: −1.96, 95% CI: −3.85 to −0.07], $p = 0.042$.	PD exhibited reduced DLPFC activity in the iCSRT and reduced SMA and premotor cortex activity in the SST.
Plenger (*82*)	**TBI**: *n* = 14 HC: *n* = 13	2 Stroop task: dot color naming task, incongruent task	Bilateral frontal, temporal, and mid to inferior parietal	TBI demonstrated greater [oxy-Hb] increases from resting baseline in bilateral DLPFC and VLPFC compared to the HC.	TBI had a significant increase in [oxy-Hb] in bilateral frontal regions during the color naming task.
Chang (*81*)	**TBI**: *n* = 30 HC: *n* = 55	The Stroop tasks; the n-back tasks	Prefrontal	Significant differences in [oxy-Hb] levels were observed. the Stroop task: Ch 3, 4, 8, 9, 11, 12, 14, 15, 21; the 2-back task: Ch 2, 3, 7, 9, 10, 11, 14, 15, 18, 21, 22.	TBI exhibited lower but more widespread activation during the 2-back and Stroop color word consistency tasks.

Abbreviation: AD: Alzheimer's disease. HC: healthy control. BLOT: Benton Line Orientation Task. [oxy-Hb]: oxygenated hemoglobin. WM: working memory. PEW: positive emotional words. FDR: false discovery rate. MCI: mild cognitive impairment. VFT: verbal fluency task. FC: functional connectivity. PFC: prefrontal cortex. ROI: region of interest. SD: standard deviation. MNES: Mini-Mental State Examination. LOL: left occipital lobe. tDCS: transcranial Direct Current Stimulation. PSCI: Post-stroke cognitive impairment. STR: patients without cognitive impairment after stroke. CDT: Clock drawing test. DST: Digit span test. CBT: Corsi Block-tapping test. RHD: patients with PSCI who have right hemisphere damage. CPT: continuous performance test. NPSCI: Non-PSCI. YA: young adults. OA: older adults. PD: Parkinson's Disease. CSRT: choice stepping reaction time task. iCSRT: inhibitory choice stepping reaction time. SST: a Stroop stepping test. SMA: supplementary motor areas. MD: mean difference. CI: confidence interval. TBI: traumatic brain injury. DLPFC: dorsolateral prefrontal cortex. VLPFC: ventrolateral prefrontal cortex. MS: multiple sclerosis.

Table 2. Summary of fNIRS applications on neurological diseases (continued)

Reference	Research object	Activation Task	Brain Region	Results	Evidence
Stojanovi (*85*)	**MS**: $n = 13$ HC: $n = 12$	The n-back WM task	Prefrontal	MS showed increased [oxy-Hb] in the left superior frontal gyrus from 0-back to 1-back, followed by a decrease from 1-back to higher loads.	MS showed increased brain activation during the lower difficulty task and decreased brain activation during the higher difficulty tasks compared with the HC.

Abbreviation: AD: Alzheimer's disease. HC: healthy control. BLOT: Benton Line Orientation Task. [oxy-Hb]: oxygenated hemoglobin. WM: working memory. PEW: positive emotional words. FDR: false discovery rate. MCI: mild cognitive impairment. VFT: verbal fluency task. FC: functional connectivity. PFC: prefrontal cortex. ROI: region of interest. SD: standard deviation. MNES: Mini-Mental State Examination. LOL: left occipital lobe. tDCS: transcranial Direct Current Stimulation. PSCI: Post-stroke cognitive impairment. STR: patients without cognitive impairment after stroke. CDT: Clock drawing test. DST: Digit span test. CBT: Corsi Block-tapping test. RHD: patients with PSCI who have right hemisphere damage. CPT: continuous performance test. NPSCI: Non-PSCI. YA: young adults. OA: older adults. PD: Parkinson's Disease. CSRT: choice stepping reaction time task. iCSRT: inhibitory choice stepping reaction time. SST: a Stroop stepping test. SMA: supplementary motor areas. MD: mean difference. CI: confidence interval. TBI: traumatic brain injury. DLPFC: dorsolateral prefrontal cortex. VLPFC: ventrolateral prefrontal cortex. MS: multiple sclerosis.

right hemisphere connectivity. These results suggest that disruptions in functional neural connectivity during different cognitive processes may contribute to the poor performance on WM tasks observed in individuals with ASD (Figure 3).

Attention deficit hyperactivity disorder (ADHD) is one of the most common developmental disorders. ADHD is characterized by persistent inattention and hyperactive impulsive symptoms (*104*). Some researchers (*105*) have explored the method of distinguishing between children with ADHD and TD children based on fNIRS. Insufficient activation of the right prefrontal lobe as assessed by fNIRS was found to serve as a potentially valid biomarker for classifying children with ADHD at the individual level (Figure 3).

7. Application of fNIRS in the rehabilitation of cognitive impairment

The frequent occurrence of neurological and psychiatric diseases is often accompanied by a high incidence of cognitive impairment, which is one of the most significant functional disabilities affecting patients, alongside motor disorders, thereby impacting daily life. Consequently, early diagnosis and rehabilitation evaluation of cognitive impairment have become increasingly important. fNIRS, a robust tool for assessing brain self-regulation, plays a pivotal role in the early diagnosis and evaluation of cognitive impairment. Yoo *et al*. demonstrated the utility of fNIRS in distinguishing patients with MCI from healthy controls, successfully identifying differences in 15 individuals with MCI and 15 age-matched healthy participants. This study highlights the potential of fNIRS as a novel approach for the early diagnosis of AD (*106*). In clinical practice, symptom assessment for patients with depression and SCZ primarily relies on standardized scales. In a study by Vural Keleş and colleagues, participants were stratified into high-score and low-score groups based on their Beck Depression Inventory scores. The authors compared WM performance and hemodynamic changes between the groups. While no significant differences in WM performance were observed, fNIRS analysis revealed significantly greater activation in the right frontal lobe of the high-score group compared to the low-score group, providing novel insights into the neurophysiological underpinnings of depression (*107*). The diagnosis of ADHD is predominantly based on clinical observation and behavioral assessment scales, which can be subjective (*108*). To address this limitation, researchers have explored the use of fNIRS for ADHD diagnosis. Crippa *et al*. demonstrated significant differences in brain activation levels between children with ADHD and healthy controls, achieving a diagnostic accuracy exceeding 80% (*109*). Furthermore, the capacity of fNIRS to provide real-time monitoring of cerebral hemodynamics offers a valuable complement

Table 3. Summary of fNIRS applications on Psychiatric diseases

Reference	Research object	Activation Task	Brain Region	Results	Evidence
Kondo (*88*)	**MDD**: $n = 25$ HC: $n = 25$	The image recall task with pleasant and unpleasant image	Forehead and temporal	During the unpleasant image task, [Oxy-Hb] increased significantly in the bilateral frontal-temporal region of HC ($q = 0.05$, αFDR > 0.025) but not in MDD.	MDD had a significantly lower [Oxy-Hb] than HC in the bilateral frontal region during the unpleasant condition.
Downey (*89*)	**Depression**: $n = 18$ HC: $n = 51$	The category VFT; WM n-back task	Frontal	In the n-Back task, patients exhibited a significant [Oxy-Hb] decrease over time ($F_{(5,85)}=5.310$, $p = 0.008$).	Depressed patients had bilaterally lower frontal [Oxy-Hb] responses to the cognitive tasks compared with HC.
Ishii (*91*)	**MDD**: $n = 29$ HC: $n = 29$	The word production task	Frontal to temporoparietal	Significantly smaller [Oxy-Hb] increase at 12 channels, especially in the left PFC (Ch 4, 6, 9).	MDD showed significantly smaller activation than the controls in the PFC area and inferior parietal area during the word production task, especially in the left area.
Liu (*90*)	**MDD**: $n = 72$ HC: $n = 74$	The letter VFT	Prefrontal	Mean connectivity: MDD = 0.303, HC = 0.400; $t = -15.586$, $p < 0.001$.	MDD had significantly less cortical activation in the hemodynamic responses of [Oxy-Hb] and lower mean channel-to-channel connectivity strength than HC.
Kameyama (*92*)	**BD**: $n = 17$ **MDD**: $n = 11$ HC: $n = 17$	The letter VFT; The right-finger-tapping task	Frontal and temporal	BD and MDD exhibited reduced early task activation, but BD demonstrated significant late-task increases in four frontal channels.	BD and MDD showed by preserved but delayed and reduced frontal lobe activation, respectively.
Nishimura (*93*)	**DBD**: $n = 16$ **HBD**: $n = 11$ HC: $n = 12$	The letter VFT	Prefrontal	Significant group differences in 12 channels across bilateral DLPFC, VLPFC, and right anterior temporal cortex (FDR-corrected $p < 0.05$). HBD had larger [Oxy-Hb] changes than DBD in Ch 49 (left DLPFC).	BD exhibited significantly lower activation during the VFT than HC in the broader bilateral PFC. Hemodynamic changes in the left DLPFC in the HBD were significantly larger than those in the DBD.
Koike (*95*)	**SCZ**: $n = 26$ HC: $n = 26$	The n-back task	Prefrontal	SCZ showed significant activation during the 1-back task at 19 channels and during the 2-back task at 24 channels.	SCZ showed reduced activation in the PFC but more extensive activation areas.
Noda (*96*)	**SCZ**: $n = 30$ HC: $n = 30$	The letter VFT	Prefrontal/ temporal	In SCZ, [oxy-Hb] aberrant re-increase was observed immediately after the VFT period following a rapid decrease (visual inspection).	SCZ in the VFT period after the end of [oxy – Hb] abnormal immediately after falling rapidly rise again.
Kumar (*97*)	**SCZ**: $n = 15$ HC: $n = 22$	The n-back task	Frontal	The right PFC showed a trend of inverted U-shaped activation with higher levels during 1-back > 0-back ($p = 0.09$) and 1-back > 2-back ($p = 0.07$).	A delayed but compensatory hyperactivation of right frontopolar cortex noted in SCZ may underlie the WM deficit.

Abbreviation: MDD: major depressive disorder. HC: healthy control. [oxy-Hb]: oxygenated hemoglobin. FDR: false discovery rate. VFT: verbal fluency task. PFC: prefrontal cortex. BD: bipolar disorder. DBD: depressed bipolar disorder. HBD: hypomanic bipolar disorder. DLPFC: dorsolateral prefrontal cortex. VLPFC: ventrolateral prefrontal cortex. SCZ: schizophrenia. WM: working memory. ADHD: attention deficit hyperactivity disorder. ASD: autism spectrum disorder. WCST: Wisconsin Card Sorting Task. FC: functional connectivity.

Table 3. Summary of fNIRS applications on Psychiatric diseases (continued)

Reference	Research object	Activation Task	Brain Region	Results	Evidence
Monden (*105*)	**ADHD**: $n = 30$ HC: $n = 30$	A go/no-go task	Prefrontal	HC showed significant [oxy-Hb] increases at Ch 5 (d = 0.741), Ch 6 (d = 0.755), and Ch 10 (d = 1.046), while ADHD showed no significant activation in these channels.	The right prefrontal hypoactivation assessed by fNIRS would serve as a potentially effective biomarker for classifying ADHD children at the individual level.
M. M. Y. Chan (*102*)	**ASD**: $n = 29$ HC: $n = 26$	The WCST	Prefrontal	In ASD, FC was lower in the right lateral PFC during acquisition ($p = 0.005$) and in the bilateral PFC during application (right: $p = 0.006$; left: $p = 0.006$).	ASD individuals showed significantly lower prefrontal FC than typical developing individuals during WCST.
Han (*103*)	**ASD**: $n = 22$ HC: $n = 24$	The n-back task	Prefrontal	In ASD, a trend toward significance in right medial PFC connectivity was observed between 0-back and 1-back ($p = 0.030$, uncorrected), with no significant effects on the left.	A disruption of functional neural connections that support different cognitive processes may underlie poor performance in WM tasks in ASD.

Abbreviation: MDD: major depressive disorder. HC: healthy control. [oxy-Hb]: oxygenated hemoglobin. FDR: false discovery rate. VFT: verbal fluency task. PFC: prefrontal cortex. BD: bipolar disorder. DBD: depressed bipolar disorder. HBD: hypomanic bipolar disorder. DLPFC: dorsolateral prefrontal cortex. VLPFC: ventrolateral prefrontal cortex. SCZ: schizophrenia. WM: working memory. ADHD: attention deficit hyperactivity disorder. ASD: autism spectrum disorder. WCST: Wisconsin Card Sorting Task. FC: functional connectivity.

to traditional scale-based assessments in rehabilitation contexts.

Beyond its diagnostic applications, fNIRS is also widely used in evaluating the efficacy of treatments for cognitive impairment, often in combination with various neural modulation techniques such as tDCS (*69*) and MNES (*70*). By enabling real-time and repeated dynamic monitoring of brain function, fNIRS allows for the observation of individual cortical responses, thereby facilitating the determination of optimal stimulation parameters, including intensity, frequency, and duration. This approach is crucial for evaluating rehabilitation outcomes and optimizing intervention strategies.

8. Conclusions

Cognition fundamentally relies on the normal functioning of the cerebral cortex. Any factors that disrupt the structure or function of the cerebral cortex can lead to cognitive impairment, with common causes including neurodegenerative and psychiatric diseases. Different forms of cognitive impairment are often interconnected, such that deficits in one domain may give rise to abnormalities in others, making the diagnosis and treatment of cognitive impairment particularly challenging (*110*). fNIRS, as a non-invasive and portable neuroimaging modality, is particularly well-suited for studying hemodynamic responses in the cortex during cognitive tasks in populations such as children, older adults, and individuals with unique needs. Additionally, fNIRS holds significant promise for advancing cognitive neuroscience in real-world contexts. Recent advancements in fNIRS research have begun to elucidate the complex relationships between cognitive processes—such as learning, memory, and language—and regional CBF and metabolism. Beyond its applications in cognitive research, fNIRS has shown potential in investigating brain functional changes induced by physical activity. The application of fNIRS in rehabilitation is particularly noteworthy for its ability to provide precise imaging-based evidence to guide intervention planning. A key to improving rehabilitation outcomes lies in the development of targeted clinical interventions based on brain function remodeling. In future clinical practice, the development of comprehensive brain function assessment frameworks based on fNIRS may allow real-time monitoring of cortical responses induced by rehabilitation, thereby providing insights into neural plasticity. Advanced analysis of fNIRS data could not only deepen our understanding of the mechanisms underlying this technology but also inform the design of personalized rehabilitation plans, offering valuable perspectives on treatment efficacy and prognosis.

However, its current limitation in penetrating deep brain structures, restricts its full potential. fNIRS relies on light penetration and reflection, typically reaching

a depth of 1.5 to 2cm. Consequently, it is unable to capture comprehensive structural images or anatomical information (*12*). Its primary utility lies in studying metabolic activities in superficial areas, rather than deep structures like the hippocampus or amygdala (*111*). To unlock the full capabilities of fNIRS, it is crucial to overcome this limitation and extend its application to explore deep brain function. Consequently, the integration of fNIRS with other imaging modalities is an inevitable trend in its development. Multimodal imaging approaches offer a more comprehensive and systematic assessment of brain function. Motion artifacts affect most imaging techniques, including fNIRS. However, fNIRS exhibits relatively higher tolerance to motion artifacts compared to other neuroimaging methods, making it suitable for use during physical activities (*37*). To address motion artifacts in fNIRS studies, researchers have devised various methods to minimize signals originating from non-brain tissue activities. Among these methods, short-channel subtraction has demonstrated notable efficacy in reducing extracerebral responses and is often regarded as the "gold standard" (*67*). Despite its application across multiple research domains, the absence of standardized protocols for data processing and analysis in fNIRS studies significantly hinders cross-study comparisons (*15,42*).

A considerable body of research on fNIRS has primarily focused on the blood flow and metabolism within brain regions associated with various types of cognitive impairment. However, the understanding of the brain network mechanisms underlying fNIRS remains limited, with divergent theoretical perspectives, particularly regarding brain network connectivity and the synergistic interactions between brain regions. Consequently, there is substantial potential for further exploration and refinement of fNIRS in this context. This review provides an overview of the application of fNIRS in cognitive impairment associated with various diseases and highlights its potential in the early detection and diagnosis of AD and MCI. By measuring oxygenation levels in the frontal, temporal, and parietal lobes during cognitive tasks and comprehensively analyzing the brain functional connectivity, fNIRS can provide valuable insights into the study of cognitive impairment related to central nervous system diseases. This review aims to stimulate further research in the field of fNIRS, facilitating the exploration of neural mechanisms underlying cognitive activity. It is anticipated that with ongoing technological advancements, fNIRS will evolve into a more user-friendly research tool with expanded clinical applications.

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