**TOPICAL REVIEW**

# Non-invasive transcranial electrical brain stimulation guided by functional near-infrared spectroscopy for targeted neuromodulation: a review

To cite this article: Keum-Shik Hong *et al* 2022 *J. Neural Eng.* **19** 041001

Journal of Neural Engineering

TOPICAL REVIEW

# Non-invasive transcranial electrical brain stimulation guided by functional near-infrared spectroscopy for targeted neuromodulation: a review

RECEIVED
16 February 2021

REVISED
27 July 2022

ACCEPTED FOR PUBLICATION
29 July 2022

PUBLISHED
17 August 2022

Keum-Shik Hong[1,2,*], M N Afzal Khan[1] and Usman Ghafoor[1]

[1] School of Mechanical Engineering, Pusan National University, Busan 46241, Republic of Korea
[2] Department of Cogno-Mechatronics Engineering, Pusan National University, Busan 46241, Republic of Korea
[*] Author to whom any correspondence should be addressed.

**E-mail:** kshong@pusan.ac.kr

**Keywords:** functional-near infrared spectroscopy (fNIRS), neuromodulation, electrical stimulation, hemodynamic response, transcranial direct current stimulation (tDCS), transcranial alternating current stimulation (tACS)

## Abstract

One of the primary goals in cognitive neuroscience is to understand the neural mechanisms on which cognition is based. Researchers are trying to find how cognitive mechanisms are related to oscillations generated due to brain activity. The research focused on this topic has been considerably aided by developing non-invasive brain stimulation techniques. The dynamics of brain networks and the resultant behavior can be affected by non-invasive brain stimulation techniques, which make their use a focus of interest in many experiments and clinical fields. One essential non-invasive brain stimulation technique is transcranial electrical stimulation (tES), subdivided into transcranial direct and alternating current stimulation. tES has recently become more well-known because of the effective results achieved in treating chronic conditions. In addition, there has been exceptional progress in the interpretation and feasibility of tES techniques. Summarizing the beneficial effects of tES, this article provides an updated depiction of what has been accomplished to date, brief history, and the open questions that need to be addressed in the future. An essential issue in the field of tES is stimulation duration. This review briefly covers the stimulation durations that have been utilized in the field while monitoring the brain using functional-near infrared spectroscopy-based brain imaging.

## 1. Introduction

Non-invasive brain stimulation is one of the most explored topics of the current era and has recently become more well-known; the technique has been applied in clinical and experimental settings. The concept of brain stimulation has existed for quite a long time; however, its use in the field of neuroscience-based research is no older than a decade (Zaghi *et al* 2010, Patel *et al* 2020). Recently, non-invasive brain stimulation has been used in many studies, including both patients and healthy subjects. In this field, there are several different approaches. Among these techniques, the most commonly used techniques are transcranial magnetic stimulation (TMS) and transcranial electrical stimulation (tES) (Yang *et al* 2021). tES is further categorized into transcranial direct current stimulation (tDCS) and transcranial alternating current stimulation (tACS).

In the case of TMS, the human brain is exposed to a strong magnetic field for a concise time interval (usually less than a millisecond). A current is generated in cortical neurons due to the sudden exposure to this strong magnetic field (Hallett 2000). In the case of tES, a small electrical current (1 mA to 2 mA) is applied to the subject's scalp (Nitsche and Paulus 2000, Yaqub *et al* 2018, 2021). The membrane potential or specific frequencies changes as soon as a portion of the applied current reaches the brain (Antal and Herrmann 2016, Vogeti *et al* 2022). tES has recently gained popularity upon its safety in most individuals, because most people can tolerate the stimulation (Woods *et al* 2016, Clark *et al* 2020, McKendrick *et al* 2020). Its portability and

relative inexpensiveness give tES another advantage over other brain stimulation techniques. The utilization of tES ranges from studying the process of change in the organization of neurons in the normal brain (Fröhlich *et al* 2015, Kuo and Nitsche 2015, Prehn and Flöel 2015, Berger *et al* 2018) to studying the neuroplasticity induced by stimulation (Karabanov *et al* 2015, Wessel *et al* 2015, Wang *et al* 2021). Despite advances made in tES-based non-invasive brain stimulation, several challenges remain unaddressed. The most critical challenge is understanding how to target tES in a specific brain area so that it can efficiently interact with neurons and enhance neuronal processes. This enhancement can be monitored later by measuring brain functions during memory, motor control, perception, and/or attention tasks. Another main limitation is the lack of studies that suggest the temporal aspect and brain area specificity, that is, how long the stimulation period should be and which brain area is most suitable for stimulation.

A set of neuroimaging modalities exists that help detects and monitor brain impairments. These neuroimaging technologies can be divided into invasive, partially invasive, and non-invasive techniques. Non-invasive brain imaging techniques are preferred over the other two types because they do not include any of the risks of surgery, making them safer to use. Commonly used methods to acquire brain signals noninvasively include electroencephalography (EEG), functional near-infrared spectroscopy (fNIRS), functional magnetic resonance imaging (fMRI), magnetoencephalography, radioactive tracer-based positron emission tomography (PET), and gamma emission-based single-photon emission computed tomography (SPECT) (Nicolas-Alonso and Gomez-Gil 2012, Ikeda *et al* 2020, Legrand *et al* 2020, Tian *et al* 2020, Khan *et al* 2022). These technologies have led to tremendous advancements in the field of non-invasive neuroimaging. These modalities can be compared based on their price, portability, and resolution (temporal and spatial). To this end, fMRI, PET, and SPECT have the best spatial resolution; however, these techniques are restricted to the lab environment because of the size of the equipment and lack of mobility. Moreover, these modalities are very prone to motion artifacts, and in the case of PET and SPECT, there is a risk associated with the use of radioactive material. In addition, these modalities have very low temporal resolutions. Although EEG outperforms all the imaging approaches mentioned above, with better temporal resolution but poor spatial resolution. One of the major drawbacks of most techniques discussed above is that none of them can be used alongside electrical stimulation because these technologies are prone to electric and magnetic field disruption. Based on the recent review, functional MR imaging is being used to benefit tDCS studies in three different ways: study design, outcome evaluation at the neural network level, and serving as potential bio-markers for responsiveness to tDCS (Esmaeilpour *et al* 2020).

On the other hand, during the last decade, fNIRS has proven to be a reliable method for monitoring the brain during neurostimulation. Human blood is composed of several different elements, among which oxygenated hemoglobin (HbO) and deoxygenated hemoglobin (HbR) are most sensitive to light, in the wavelength between 650 nm and 1000 nm. When some neuronal activity occurs in the brain, the local concentrations of HbO and HbR change due to neurovascular coupling. Therefore, light in the spectrum above is utilized to measure temporal changes in the local concentrations of HbO and HbR (Zafar and Hong 2020). Light is shone through several layers of the scalp and skull until it finally reaches the brain. Some of the incident light is absorbed by the brain, while some are scattered. This scattered light is then detected with the help of appropriately placed detectors on the scalp. Traditional fNIRS systems utilize two different wavelengths to detect blood chromophores; however, more than two wavelengths have also been proposed. Several studies have utilized fNIRS for brain imaging in which almost all brain areas have been investigated. A recent study has also shown that functional connectivity of the brain due to acupuncture can be monitored using fNIRS (Ghafoor *et al* 2019). Along with monitoring for healthcare, fNIRS has proven to be a viable tool in developing brain-computer interfaces to help physically disabled people (Hong and Yaqub 2019, Hong *et al* 2020, Khan *et al* 2020, Khan and Hong 2021, Zafar and Hong 2018). The field of brain computer interface has recently gained popularity with the advent of latest sophisticated classification techniques like neural networks (Bennett *et al* 2021, Oh and Jo 2021, Petrosyan *et al* 2021, Sattar *et al* 2021, Xie *et al* 2021). A pictorial depiction of the comparison of the non-invasive imaging modalities is shown in figure 1.

We adopted a search strategy to unveil almost all research conducted in the fNIRS-tES protocol. The electronic search was performed in the Web of Science using logical combinations of the following keywords: ('tDCS' OR 'transcranial direct current stimulation' AND 'fNIRS' OR 'functional NIRS' OR 'functional near-infrared spectroscopy' AND 'tACS' OR 'transcranial alternating current stimulation'). The research database was searched from inception to 1 February 2022, with restrictions on studies in English. Original studies of functional NIRS in combination with tDCS and tACS were included in this review. Since the pioneer and ongoing work on tDCS and tACS in combination with fMRI, EEG, or behaviorally has been exclusively researched, it was difficult to avoid some crucial studies within the explanation of tES or where necessary. This study focuses on the brief review of tES leading to the techniques

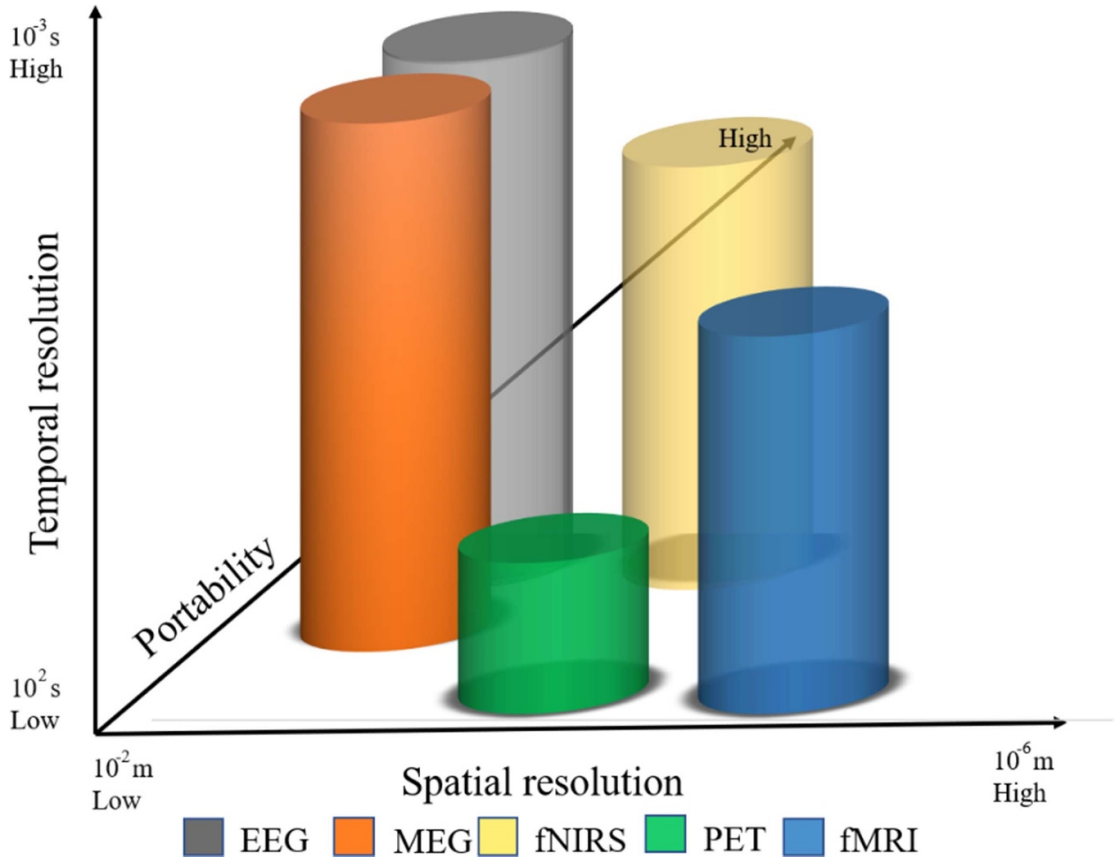


**Figure 1.** Comparison of different brain imaging modalities on the basis of spatial resolution, portability, and temporal resolution. MEG: magnetoencephalography, EEG: electroencephalography, fNIRS: functional near-infrared spectroscopy, PET: radioactive tracer-based positron emission tomography, fMRI: functional magnetic resonance imaging.

and biophysics, followed by a primary focus of the overview of studies conducted with the fNIRS-tES protocol. Finally, the shortfalls in the field and future directions are discussed.

## 2. Non-invasive tES

The use of electrical brain stimulation in both science and medicine stretches back to the late 19th century. The early applications of high-intensity tES (Lang *et al* 1969, Toleikis *et al* 1974) provided the basis for subsequent studies, suggesting that the application of weak currents to the scalp may also induce behavioral effects, but without side effects or conscious awareness of stimulation (Nitsche and Paulus 2001). The low cost, portability, and potential home applications of tES have led to a proliferation of human trials relative to other non-invasive neuromodulatory techniques, such as TMS and ultrasound stimulation (Liu *et al* 2012, Kasschau *et al* 2016). tDCS and tACS are the two most widely described transcranial electrical current stimulation methods in the literature (Polania *et al* 2018). Transcranial random noise stimulation (tRNS) is also an electrical stimulation type but rarely applied, compared to tDCS and tACS, specifically with fNIRS. Different neurophysiological responses may emerge due to the change in electrical characteristics. The effects of tDCS/tACS on the brain guided by fNIRS in combined tES-fNIRS protocols are the subject of this review.

### 2.1. tDCS

tDCS is a type of non-invasive brain stimulation that has been employed in a variety of populations (Cappon *et al* 2016b, Berryhill and Martin 2018, Yaqub *et al* 2018, Figeys *et al* 2021). It delivers direct electrical currents between two electrodes (anode and cathode), modulating the neuron's excitability by changing the potential of the resting neuronal membrane. The change in excitability direction after tDCS depends mainly on electrode mounting. In contrast, many studies have recently discovered that stimulation parameters (such as duration, intensity, frequency, the position of the electrode, and control settings) in addition to tDCS polarity can modulate the outcome of the tDCS effect (Horvath *et al* 2015, Jamil *et al* 2017). tDCS has been proven to have beneficial effects in several neurological disorders, such as stroke (Fregni *et al* 2005, Hummel *et al* 2005, Cattagni *et al* 2019, Doost *et al* 2019, Feil *et al* 2019, Kindred *et al* 2019, Mazzoleni *et al* 2019), refractory epilepsy (Meiron *et al* 2019, Yang

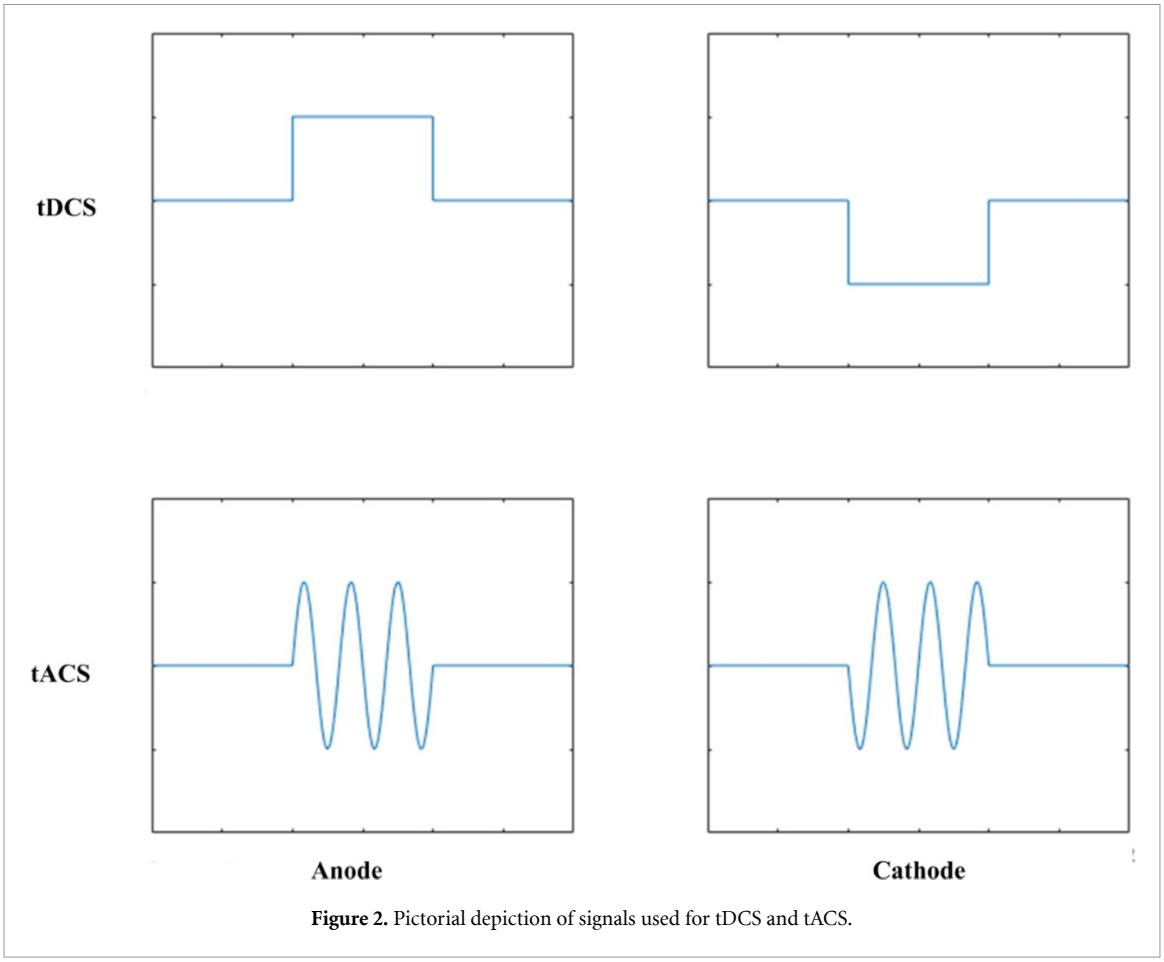


**Figure 2.** Pictorial depiction of signals used for tDCS and tACS.

*et al* 2019), and chronic depression (Fricová *et al* 2019, Iannone *et al* 2019). Other disorders treated using tDCS include drug cravings (Eskandari *et al* 2019, Martinotti *et al* 2019, Alizadehgoradel *et al* 2020, Holla *et al* 2020, Malandain *et al* 2020, Verveer *et al* 2020, Alizadehgoradel *et al* 2021, Dubuson *et al* 2021, Gaudreault *et al* 2021, Perri and Perrotta 2021, Xu *et al* 2021c, Pedron *et al* 2022), fibromyalgia (Andrade *et al* 2018, Santos *et al* 2018, Yoo *et al* 2018, Kang *et al* 2020, Arroyo-Fernández *et al* 2021, Fregni *et al* 2021, Matias *et al* 2022), gambling disorder (Salatino *et al* 2021), and traumatic spinal cord injury (Chari *et al* 2017, Cortes *et al* 2017, Hofer and Schwab 2019, Kumru *et al* 2020).

### 2.2. tACS

In 2008, the effects of tACS were first described frequency-dependent way (Antal *et al* 2008). Feurra *et al* (2011) investigated the effect of tACS on evoked potentials and discovered that 20 Hz tACS had a modulatory effect. These findings imply that tACS has frequency-dependent effects and that the processes are distinct from tDCS. The existence of frequency-dependent effects suggests that tACS may entrain cortical oscillations. The phase and frequency of brain oscillations are altered to follow the external stimulus when a brain oscillation is entrained (Helfrich *et al* 2014, Vosskuhl *et al* 2015). The frequency range surrounding a neural oscillator's inherent frequency determines whether it follows the externally produced tACS frequency. Plastic-related changes in oscillatory brain activity can endure for a long period following stimulation. The resting-state observations following tACS were used in additional and essential physiological studies (Ghafoor *et al* 2022). Moreover, tACS can influence neural oscillations in the brain during mental tasks. The tACS application allows contact with brain oscillations, allowing for modification of the latter via a 0.5–2 mA level electric current adjusted to the rhythms of endogenous oscillations via the scalp. The effects of tACS on working memory capacity, perception, multitasking, motor control, and learning have been studied extensively (Chander *et al* 2016, Kasten and Herrmann 2017). In tACS, AC signals need not be sinusoidal but can be rectangular or even have more complex forms (Herrmann *et al* 2013). Examples of an AC signal used in tACS and a DC signal used in tDCS are shown in figure 2.

Although the tRNS (Chenot *et al* 2022) is another significant non-invasive stimulating approach, the authors tried to circumvent it because this review focuses on combined protocol with fNIRS, and no study of combined fNIRS and tRNS is available in the literature.

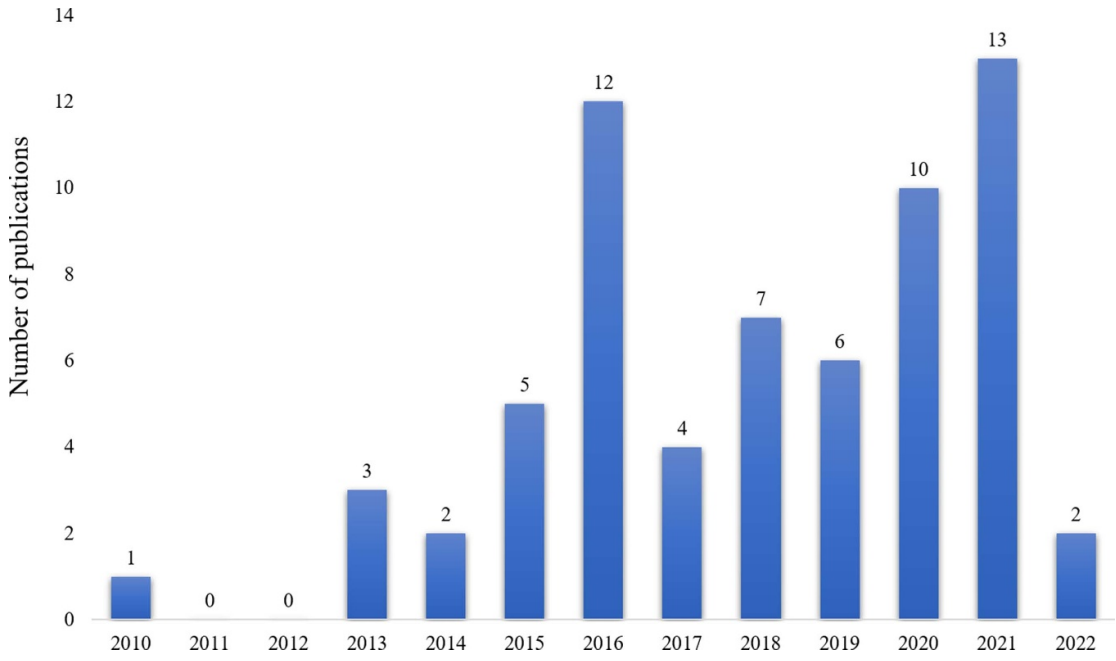


**Figure 3.** Comparison of the number of fNIRS-based studies conducted in the past decade that utilized electrical stimulation.

## 3. Combined fNIRS-tES studies

Different stimulation durations have been used in different brain areas in the field of tES. While utilizing fNIRS as a brain imaging modality, almost all brain areas have been monitored to determine the effect of tES. Although fNIRS is a relatively new technique, many studies using fNIRS have been conducted to determine the effectiveness of tES. Figure 3 shows the number of studies conducted yearly in the last decade. While conducting these studies, different brain areas were monitored, as mentioned earlier. Therefore, depending on the brain area, different analysis parameters were used to monitor the effectiveness of tES. Figure 4 illustrates the comparison of different parameters used in some of these studies that utilized tDCS for stimulation. During these experiments, fNIRS data were sampled at different instances. Some of these studies focused on the long-term effects of tES, while others focused on neuronal changes during stimulation. Figure 5 gives an overview of the studies that used different time instances to measure the hemodynamic response. The brain areas mainly under focus in fNIRS studies monitoring the effects of tES include the frontal, occipital, and parietal lobes. Different stimulation durations were used for each of these brain areas, as shown in figure 6.

### 3.1. Studies on frontal region

Studies of the prefrontal cortex (PFC) utilizing fNIRS began with a study investigating the effect of tDCS of the PFC (Merzagora *et al* 2010). In this study, active stimulation was given to 12 subjects and sham stimulation to 10 subjects for 10 min. The study results showed that, in comparison to sham stimulation, anodal stimulation increased the amount of activation in the PFC. To investigate the effects of tDCS, a study in 2015 utilized a working memory task to assess brain activation (Jones *et al* 2015). The participants' PFC was stimulated at an intensity of 1.5 mA. The study results indicate that tDCS can enhance the cognitive abilities of a person. Jones *et al* stimulated the left PFC of 24 healthy subjects to determine the effect of tDCS on performance in working memory tasks. The stimulation was performed for 10 min at an intensity of 1.5 mA. The study concluded that stimulation improved working memory performance. A study conducted to investigate the effects of tDCS on drug-craving revealed that tDCS offers a promising solution for the treatment of relapse prevention (Kroczek *et al* 2016). Stephens *et al* (2016) demonstrated the effectiveness of tDCS for maintaining cognitive abilities for a long time as we grow older. While investigating the effects of tDCS on the dorsolateral PFC and frontotemporal cortex, it was found that application of tDCS had no significant effect on the amount of activation in the dorsolateral PFC when performing verbal frequency tasks (Herrmanm *et al* 2017). In the same year, a study revealed that although tDCS affects the activation of the brain in response to a contraction task, it has no significant effect on the fatigue indices (Radel *et al* 2017). A recent study by Clark and colleagues demonstrated that 18 sessions of tDCS along with walking rehabilitation are sufficient and safe for older adults. Table 1 summarizes the studies in the field of fNIRS that utilized tDCS/tACS.

Neuromodulation with tES has the potential to help people recover a variety of brain functions

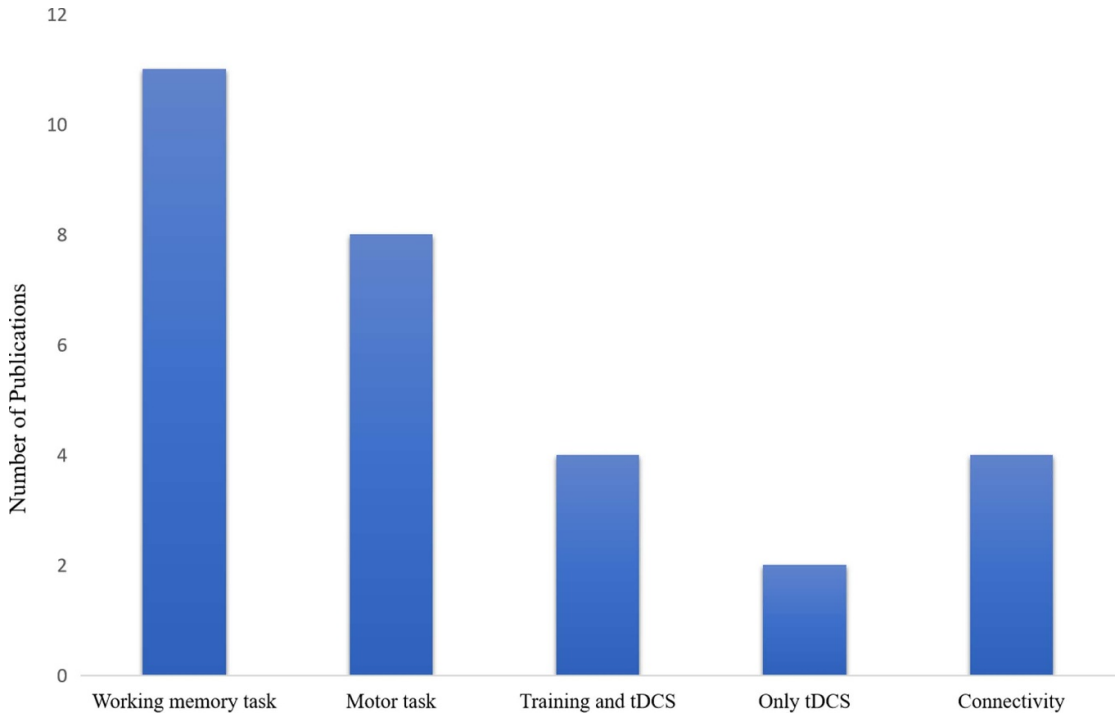


**Figure 4.** Comparison of the methods used in different fNIRS-based studies to assess the cognitive effects of transcranial direct current stimulation (tDCS).

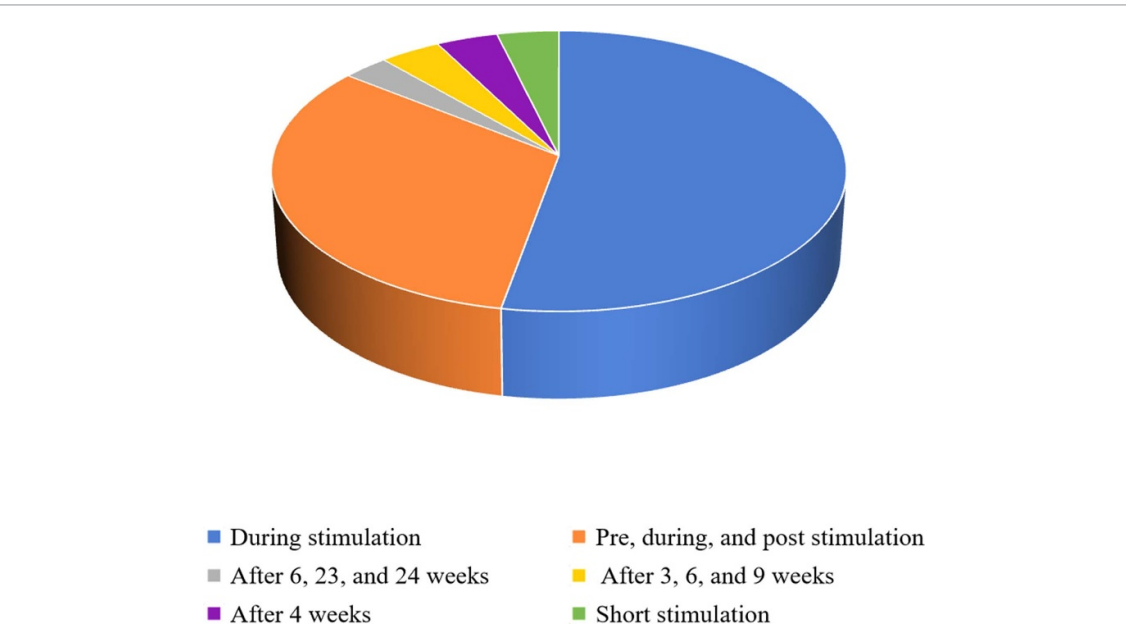


**Figure 5.** Comparison of the different times used for the monitoring of brain behavior.

that have been lost or compromised. Recently, Yaqub *et al* (2021) aimed to provide the feasibility of the proposed closed-loop strategy using the feedback from targeted functional networks in the prefrontal cortex. Moreover, the authors discussed recommended parameters feasible for deploying in the feedback loop. Moreover, due to the differences in stimulation parameters among studies, such as duration, frequency, intensity, and electrode montage, and limited information of the underlying neurophysiological mechanisms, the exact mechanism of tES-induced after-effects remains uncertain. Furthermore, due to electrical abnormalities, the accuracy of EEG data is compromised during tES. Besides, hemodynamic alterations during stimulation, particularly during tACS, are poorly understood. Hybrid fNIRS-EEG-tES can be used with either tDCS or tACS with no electro-optic intervention to evaluate the hemodynamic response during electrical stimulation. A recent combined fNIRS-tES study was conducted,

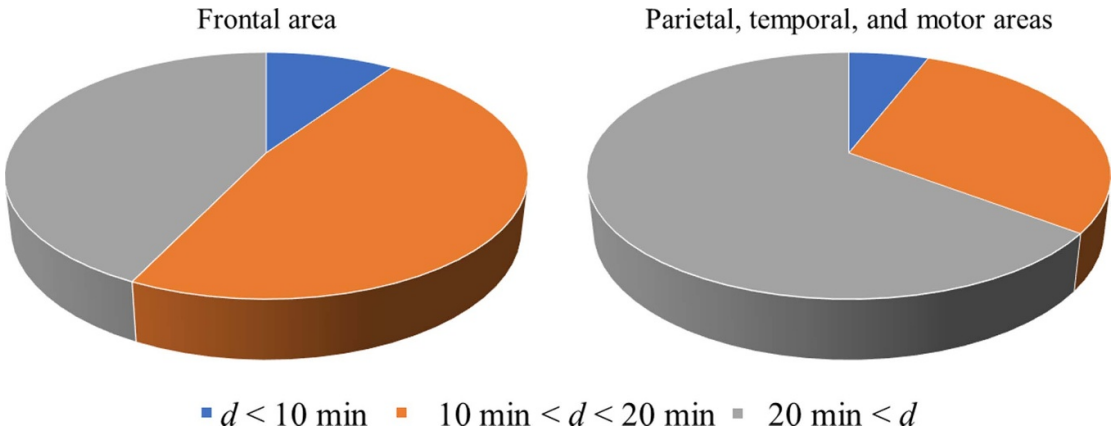


**Figure 6.** Comparison of different brain stimulation durations (*d*).

which comprehensively investigates the effects of tDCS and tACS on the PFC using fNIRS and EEG simultaneously (Ghafoor *et al* 2022). Another aspect of this study was checking the placement of high-definition montage to target both left/right PFCs simultaneously. Using fNIRS-EEG-tES, they observed enhanced prefrontal activity. In this resting state study, tDCS and tACS caused significant improvements in mean hemodynamic responses during and after stimulation periods. When tACS was compared to tDCS in between-group analyses, the mean hemodynamic responses induced by tACS were a bit lower. They used tDCS and tACS to illustrate the viability of a high-density setup in boosting hemodynamics in both sides of PFCs simultaneously. Furthermore, after tACS stimulation, there was a rise in alpha band power and a decrease in beta band power. Even though tDCS is not frequency-specific, it considerably impacted most EEG band powers.

Researchers investigated the neural correlates of stimulation-induced modulation of the ability to learn the value of future outcomes and the sequential choices necessary to achieve them (i.e. sequential decision-making) (Schommartz *et al* 2021). They revealed three findings: (a) an increased dorsolateral PFC hemodynamic response during the acquisition of sequential state transitions, (b) a tDCS-induced increase in the dorsolateral PFC hemodynamic response, but without accompanying performance-enhancing effects at the behavioral level and, and (c) a greater tDCS-induced upregulation of hemodynamic responses in the delayed reward condition.

Another study was conducted on language processing having two aims: (a) whether fNIRS could be used to detect changes in hemodynamic response in young adults with developmental language disorder after anodal high definition (HD) tDCS enhanced phonological working memory training and (b) and could be used to identify atypical hemodynamic responses in these same adults with developmental language disorder during active spoken word processing (Berglund-Barraza *et al* 2020). They concluded that individual variations in the relationship between behavior and neural patterns in a single person with a developmental language disorder might be established using fNIRS to track individual differences in changes in brain activity following working memory training. Another study was conducted on language processing having two aims: (a) whether fNIRS could be used to detect changes in hemodynamic response in young adults with developmental language disorder after anodal HD-tDCS enhanced phonological working memory training and (b) and could be used to identify atypical hemodynamic responses in these same adults with developmental language disorder during active spoken word processing (Berglund-Barraza *et al* 2020). They concluded that individual variations in the relationship between behavior and neural patterns in single person with developmental language disorder may be established using fNIRS and track individual differences in changes in brain activity following working memory training. Another pioneering tDCS research examines the influence of multiple active HD-tDCS interventions on executive functions (Lu *et al* 2021). The main results showed that nine anodal HD-tDCS sessions could improve different aspects of executive functions. They demonstrated that the enhancement of cognitive flexibility in the anodal group was significantly better than that in the sham group. Moreover, a Stroop effect-related decrease in HbO concentration in the dorsolateral PFC was observed in the anodal group but not the sham group.

### 3.2. Studies on parietal, temporal, and motor areas

Work on motor area of the brain started in 2013 (Muthalib *et al* 2013). In this study, the motor cortex in 15 healthy subjects was stimulated for 10 min and the amount of activation due to stimulation was observed in the PFC. The results of the study showed that there was no modulation due to tDCS in the muscle force production that was being monitored

**Table 1.** fNIRS-based studies conducted on the frontal area while stimulation with tDCS/tACS.

| Authors (year of publication) | Subjects under observation | No. of subjects | Stimulation duration | Intensity of stimulation | tDCS/tACS stimulation area | fNIRS measurement area | Cognitive task | Reported signals | Granular findings |
|---|---|---|---|---|---|---|---|---|---|
| Ghafoor *et al* (2022) | Healthy | 15 (1 session of tACS (10 Hz) and 1 session of tDCS) | 12 min | 1 mA | Anode: FpZ and 4 cathodes in square (4 and 6 cm) around anode | Left and right prefrontal cortices | Nil | Concentration changes in HbO and HbR EEG band power | • Post stimulation increase in HbO for both tDCS and tACS.<br>• Increase in HbO was dominant in channels near anode. |
| Yaqub *et al* (2021) | Healthy | 15 | 10 min | 1 mA | Anode: Fp2, and 4 cathodes in square around anode | Left and right prefrontal cortices | | Connectivity, graph theoretical assessment, and proposed the closed loop strategy | • Prefrontal functional connectivity enhancement throughout stimulation. |
| Lu *et al* (2021) | Healthy | 43 | 20 min (9 sessions) | 1.5 mA | Dorsolateral PFC (DLPFC) | Bilateral dorsolateral PFC | Working memory task | Concentration changes in HbO | • Repeated HD-tDCS results in cognitive flexibility enhancement.<br>• Decrease of HbO related to Stroop effect DLPFC |
| Schommartz *et al* (2021) | Healthy | 31 | 20 min | 2 mA | Dorsolateral PFC Anode: F4 Cathode: F3 | Left and right dorsolateral PFC | Three-state Markov decision task | Concentration changes in HbO | • Enhancement of hemodynamic on DlPFC in result of tDCS. |
| Berglund-Barraza *et al* (2020) | Adults with developmental language disorder | 2 | 20 min | 1 mA | Anode: Fz Cathode: four (FpZ, F7, F8, and Cz) | Brodmann's areas 10 and 46 | Working memory task | Concentration changes in HbO and HbR | • The HbO response moved within normal limits after training. |
| Clark *et al* (2020) | Healthy | 18 | 20 min | 2 mA | Anode: F4 and cathode: F3 | Prefrontal cortex | Walking | Concentration changes in HbO | • Eighteen sessions of walking rehabilitation combined with tDCS is a feasible and safe intervention for older adults. |

(Continued.)

**Table 1.** (Continued.)

| Authors (year of publication) | Subjects under observation | No. of subjects | Stimulation duration | Intensity of stimulation | tDCS/tACS stimulation area | fNIRS measurement area | Cognitive task | Reported signals | Granular findings |
|---|---|---|---|---|---|---|---|---|---|
| McKendrick *et al* (2020) | Healthy | 21 (tDCS for 11) | 15 min | 1 mA | Ventrolateral prefrontal cortex (Anode: F10 and Cathode: F2) | Broadmann's area 10, 46, 45, 44 | Working memory task | Concentration changes in HbO, HbR, and oxygenation | • tDCS can affect propensity of neurons.<br>• The nature of utilization of hemodynamics is altered by tDCS. |
| Di Rosa *et al* (2019) | Healthy | 21 | 30 min | 1.5 mA | Anode: between F3 and F7 Cathode: contralateral shoulder | Frontal and parietal regions of interest | | Concentration changes in HbO and HbR | • Working memory is enhanced by reward motivation-based anodal tDCS over left PFC.<br>• HbO in PFC is increased in older adults in result of aforementioned process. |
| Li *et al* (2019) | Patient | 26 | 20 min | 2 mA | Dorsolateral prefrontal cortex (Anode: F3 and Cathode: F4) | Left and right prefrontal cortices | | | • tDCS may improve the processing of negative emotions in PSD patients.<br>• tDCS may enhance the aerobic metabolism in the PFC, thereby improving depressive symptoms. |
| Harris *et al* (2018) | Patient | 24 | 20 min | 2 mA | M1 area | Left and right dorsolateral prefrontal cortices | | Trial protocol | • tDCS can have a long-lasting effect on balance, functional and neurophysiological outcome, and neurocognitive outcome. |
| Giovannella *et al* (2018) | Healthy | 20 | 10 min | 1 mA | Anode: AF7, and Cathode: PO8 | AF7, Af8, FT7, FT8, PO7, PO8, TP7, TP8 | Nil | Concentration changes in HbO and HbR; cerebral blood flow (CBF) | • CBF is a better indicator of hemodynamic changes under the stimulation electrode.<br>• CBF increases during and after stimulation in regions under stimulation. |

(Continued.)

**Table 1.** (Continued.)

| Authors (year of publication) | Subjects under observation | No. of subjects | Stimulation duration | Intensity of stimulation | tDCS/tACS stimulation area | fNIRS measurement area | Cognitive task | Reported signals | Granular findings |
|---|---|---|---|---|---|---|---|---|---|
| Berger *et al* (2018) | Healthy | 24 (2 session of tACS (10 Hz and 20 Hz) | 20 min | 1 mA | Parietal cortices (Anode: P3 and Cathode: P4) | Bilateral motor cortex | Bimanual coordination task | Concentration changes in HbO and EEG band power | • Decrease in HbO after tACS stimulation as compared to sham group.<br>• HbO changes in the parietal area are relevant to bimanual motor behavior. |
| Yaqub *et al* (2018) | Healthy | 15 | 10 min | 1 mA | Anode: Fp2, and 4 cathodes in square | Left and right prefrontal cortices | Nil | Concentration changes in HbO and functional connectivity | • HbO increased in result of tDCS.<br>• The increased level are maintained after tDCS. |
| Cao *et al* (2018a) | Healthy | 13 | 2 min 40 s and 8 min | 0.5 mA and 1 mA | Bilateral frontal locations (Anode: FC5 and Cathode: Fp2) | Broca's and Wernicke's areas, frontopolar, dorsolateral prefrontal cortex and premotor areas | | Functional connectivity | • fNIRS can be utilized for mapping the direction of information flow induced by tDCS. |
| Cao *et al* (2018b) | Healthy | 13 | 2 min 40 s and 8 min | 0.5 mA and 1 mA | Bilateral frontal locations (Anode: FC5 and Cathode: Fp2) | | | Directed phase transfer entropy | • Functional connectivity is significantly increased by anodal stimulation.<br>• tDCS induced significantly increased functional connectivity between Broca's area and its neighboring cortical regions |
| Narita *et al* (2018) | Diseased | 26 | 20 min | 2 mA | Anode: F3 and Cathode on FP2 | Bilaterally on prefrontal locations | Verbal frequency task | Concentration changes in HbO | • tDCS may have the ability to treat psychotic symptoms.<br>• NIRS provides biomarkers in utilization of tDCS in treatment of schizophrenia |

(Continued.)

**Table 1.** (Continued.)

| Authors (year of publication) | Subjects under observation | No. of subjects | Stimulation duration | Intensity of stimulation | tDCS/tACS stimulation area | fNIRS measurement area | Cognitive task | Reported signals | Granular findings |
|---|---|---|---|---|---|---|---|---|---|
| Borragán *et al* (2018) | Healthy | 20 | 25 min | 1.5 mA | Dorsolateral prefrontal region (Anode: F3 and Cathode: right arm) | Superior frontal cortices | Working memory TloadDback task | Cerebral oxygen exchange | • tDCS was not effective to counteract the behavioral effects of cognitive fatigue (CF).<br>• COE levels increased after CF task for sham group.<br>• In contrast, for tDCS group, CF induction significantly shifted interhemispheric oxygenation balance. |
| Hermann *et al* (2017) | Healthy | 61 | 26 min | 1 mA | Dorsolateral prefrontal cortex | Bilateral prefrontal locations | Verbal frequency task | Concentration changes in HbO and HbR | • Bilateral tDCS stimulation on DLPFC showed no effect on HbO during VFT.<br>• Increased HbR was observed in case of stimulation as compared to sham group. |
| Ehlis *et al* (2016) | Healthy | 46 | 20 min | 1 mA | Anode: Between C3, F3 and Cathode: supraorbital region | Bilateral frontotemporal regions | Verbal frequency task | Concentration changes in HbO and HbR | • Both preceding anodal and cathodal tDCS did not modulated VFT performance.<br>• Preconditioning with anodal tDCS increased brain activity during the VFT. |
| Stephens and Berryhill (2016) | Healthy | 90 | 15 min | 2 mA | Right prefrontal cortex (Anode: F4 and Cathode: Cheek) | Bilateral prefrontal locations (F3 and F4) | Working memory task | fNIRS and genotyping results | • 2 mA of tDCS induced significantly greater far transfer gains after 1 month.<br>• WM training combined with tDCS is an effective intervention that improves cognitive performance |

(Continued.)

**Table 1.** (Continued.)

| Authors (year of publication) | Subjects under observation | No. of subjects | Stimulation duration | Intensity of stimulation | tDCS/tACS stimulation area | fNIRS measurement area | Cognitive task | Reported signals | Granular findings |
|---|---|---|---|---|---|---|---|---|---|
| Kroczek *et al* (2016) | Diseased | 25 | 19 min | 2 mA | Bilaterally on prefrontal locations Anode: F3 and Cathode: Fp2 | Bilaterally on prefrontal locations (OFC, left BA46, right and left BA9) | Cigarette cue-exposure | Concentration changes in HbO and HbR and connectivity | • tDCS did not significantly alter craving or heart rate.<br>• Hemodynamics in LPFC increased in the group receiving sham stimulation. |
| Jones *et al* (2015) | Healthy | 24 | 10 min | 1.5 mA | Left prefrontal locations (anode: between F3 and F7) | Left prefrontal locations (F7 and F3) | Working memory task | oxygenated blood flow | • Ensuring that participants' incentives are high may expand cognitive benefits associated with tDCS |
| Merzagora *et al* (2010) | Healthy | 22 | 10 min | 1 mA | Bilaterally on prefrontal locations (Anode: Fp1 and Cathode: Fp2) | Prefrontal cortex | Resting state | Concentration changes in HbO and HbR | • Anodal stimulation induced a significant increase HbO compared to sham.<br>• Cathodal stimulation had negligible effects. |

through PFC activation. In the same year, another study investigated the effects of tDCS while performing a wrist flexion task (Khan *et al* 2013). fNIRS data were collected while the task was performed before, during, and after the stimulation (stimulation period, 15 min). The results from eight healthy subjects indicated that when used with tDCS, fNIRS can measure insight into how the muscles are affected by neuroplasticity. A study performed in rats showed an increase in the hemodynamic response during tDCS, and the activity started to decrease as soon as the stimulation stopped (Han *et al* 2014). In this study, the rats were stimulated for 10 min, whereas the fNIRS data were recorded during stimulation and 20 min after stimulation. The authors concluded that the stimulation parameters must be customized per subject to achieve the maximum after-effects of tDCS. While stimulating the left motor cortex, functional connectivity was compared in five healthy subjects (Yan *et al* 2015). This study provided stimulation for 5 min, which is the first study to the best of our knowledge, to check the comparatively short stimulation duration effect. The results before, during, and after stimulation were compared. The results indicated that resting-state coherence could be a helpful tool for calculating the optimal parameters for tDCS utilization. In the following year, a study conducted on 32 healthy subjects found a relationship between tDCS and the learning process (Choe *et al* 2016). The subjects were stimulated for 60 min at an intensity of 2 mA.

Takai *et al* (2016) suggested that changes occur in blood flow in the case of both anodal and cathodal tDCS. After stimulating the right primary motor area in seven healthy subjects for 20 min, the authors concluded that the effect of tDCS is limited to the brain area under-stimulation and expands to other areas of the cortex. In the same year, a study was conducted to investigate the effects of HD-tDCS relative to those of tDCS stimulation (Gözenman and Berryhill 2016). The posterior parietal cortex of 34 healthy subjects was stimulated for 20 min. The study results suggested that in comparison to tDCS, HD-tDCS had a more significant influence on the group with worse working memory. Interestingly, participants with better working memory demonstrated the opposite trend.

In order to improve lower limb strength, postural sway, and gait speed in patients with Parkinson's disease, the motor area in 42 patients underwent stimulation at 2 mA for 20 min (Hendy *et al* 2016). The results of the study demonstrate the effectiveness of the method. Muthalib *et al* (2016) extended the work on HD-tDCS and investigated its effect while performing sequential figure-tapping tasks. Interesting work in the same year proposed using a Kalman filter (Sood *et al* 2016). This filter was based on estimation using an autoregressive model. The authors proposed that this model could keep track of the coupling between EEG and fNIRS data while tDCS was applied.

Pilot research was conducted to see how a two-week tDCS therapy affected the cortical hemodynamics of a knee osteoarthritis cohort as evaluated by fNIRS (Pollonini *et al* 2020a). They suggested that fNIRS is a valid tool for objectively tracking pain in an ambulatory situation. It might be used to influence methods for improved tDCS therapy and design novel tDCS protocols. According to a finding of another similar study, the neuromodulatory intervention considerably reduced pain only in the active therapy group (Pollonini *et al* 2020b). Only the active treatment group demonstrated a substantial increase in oxyhemoglobin activation of the superior motor and somatosensory cortices when the anodal tDCS electrode was placed. Increased activity in multiple cortical areas during dual-task walking in older adults may act as a compensatory mechanism in another tDCS-fNIRS study (Orcioli-Silva *et al* 2021). Moreover, the reduction in M1 activity following active tDCS + treadmill walking with no observed gait changes suggest that tDCS improved neural efficiency.

The effect of M1-tDCS on bimanual motor skill acquisition and retention was investigated in a longitudinal study (Gao *et al* 2021). The fNIRS technology was used to record variations in brain activity during task execution. As the training progressed, they saw that tDCS reduced the performance errors. According to the trial-to-trial standard deviation analysis, the tDCS group tended to stabilize performance variability in performance error and time. After a 4 week gap, the impact of tDCS on improving performance accuracy was still there. As a result, tDCS reduced contralateral M1 and PFC activity while increasing supplemental motor area. Moreover, the activation of the middle PFC and supplemental motor area regions was negatively correlated with the performance error.

Another study (Conceição *et al* 2021) was conducted to promote greater positive effects on gait, cognition, and PFC activity while walking, compared with a stand-alone session of aerobic exercise (sham tDCS) in people with Parkinson's disease. It was observed that the addition of anodal tDCS over the PFC to a session of aerobic exercise led to immediate positive effects on gait variability, processing speed, and executive control of walking in people with Parkinson's disease. Table 2 summarizes all studies in fNIRS using tDCS/tACS of all brain areas except the frontal region.

## 4. Stimulation durations

The effects of electrode-based tDCS induced plasticity have been found to vary under certain circumstances. Duration of stimulation is one of the factors causing the variation in neuromodulatory effects of tDCS (Vignaud *et al* 2018). Considering a rapidly developing amount of tDCS studies, there is no apparent link between stimulation intensity

**Table 2.** fNIRS-based studies investigating the effect of tDCS.

| Authors (year of publication) | Subject under observation | No. of subjects | Stimulation duration | Intensity of stimulation | Stimulation area | Measurement area | Task performed | Reported signals | Granular findings |
|---|---|---|---|---|---|---|---|---|---|
| Conceição *et al* (2021) | Diseased | 20 | 20 min | 2 mA | Anode: F3/F4 (affected hemisphere) Cathode: FP2/FP1 | Brodmann areas 9, 10, and 46 | Walking | Concentration changes in HbO and HbR | • Post tDCS increase in PFC activity along with shortened reaction time was observed. |
| Gao *et al* (2021) | Healthy medical students | 12 | 10 min | 1 mA | Anode: C3 Cathode: Fp2 | Prefrontal locations, M1 and PFC, M1, and supplemental motor area | Bimanual motor task and pattern cutting | Concentration changes in HbO and HbR | • tDCS decreased error level and the variability in performance, compared to the sham group<br>• HbO in primary motor and prefrontal cortices decreased whereas increased in supplemental motor area. |
| Orcioli-Silva *et al* (2021) | Young and older adults | 23 + 21 | 20 min | 0.6 mA | Anode: Cz and between AF3 to Fp1 Cathode: Right mastoid | Brodmann areas 6 lateral/medial,4, 8, 9, 10, 45, and 46) | Treadmill walking | Concentration changes in HbO and HbR | • Motor cortex activity decreased after tDCS was given.<br>• No effect on PFC was noted. |
| Beretta *et al* (2020) | Diseased | 24 | 3 sessions | 1 mA and 2 mA | Primary motor cortex (M1) | Prefrontal locations | Postural assessment | Concentration changes in HbO | • Habituation of perturbation was evidenced independent of the stimulation conditions<br>• tDCS over M1 improved the postural response to external perturbation in PD.<br>• Better response observed for 2 mA compared with 1 mA. |
| Pollonini *et al* (2020a) | Individuals with right knee osteoarthritis | 10 | 20 min | 2 mA | Anode: C3 contralateral to the painful knee Cathode: Fp2 ipsilateral to the painful knee | Bilateral primary motor and somatosensory cortices | Thermal pain | Concentration changes in HbO and HbR | • Both HbO and HbR increased during tDCS treatment.<br>• Clinical measures of pain decrease after tDCS |

(Continued.)

**Table 2.** (Continued.)

| Authors (year of publication) | Subject under observation | No. of subjects | Stimulation duration | Intensity of stimulation | Stimulation area | Measurement area | Task performed | Reported signals | Granular findings |
|---|---|---|---|---|---|---|---|---|---|
| Pollonini *et al* (2020b) | | 19 | | 2 mA | Anode: primary motor cortex of the hemisphere contralateral to the affected knee Cathode: supraorbital region contralateral to the anode | Bilateral prefrontal cortex and the primary motor and somatosensory cortices contralateral to the thermal stimulation | Thermal stimulation | Concentration changes in HbO and HbR | • Neuromodulatory intervention significantly relieved pain only in the group receiving active treatment.<br>• Group with modulation showed increase of HbO in superior motor and somatosensory cortices. |
| Verma *et al* (2019) | Diseased | 1 | 20 min | 2 mA | Anode: F4 and Cathode: TP4 | Bilateral temporal cortical area | Auditory task | Concentration changes in HbO | • Improvement in tinnitus symptoms after tDCS.<br>• Improvement in functional cortical activity as assessed by fNIRS in chronic tinnitus after tDCS. |
| Besson *et al* (2019) | Healthy | 15 | 20 min | 2 mA | Left M1 Anode: 1, Cathodes: 4 | Left M1 | Sequential tapping of the index, middle, ring and fourth finger against the thumb | Concentration changes in HbO and HbR | • Functional targeting of motor task-concurrent with tDCS is likely more effective at producing changes in sensorimotor cortex activation.<br>• The effects lasted 30 min after stimulation. |
| Muthalib *et al* (2018) | Healthy | 13 | 10 min | 2 mA | Left M1 Anode: 1 Cathodes: four placed around anode | Bilateral M1 | Nil | Concentration changes in HbO | • Increase of HbO was observed in the surroundings of tDCS electrodes. |

(Continued.)

**Table 2.** (Continued.)

| Authors (year of publication) | Subject under observation | No. of subjects | Stimulation duration | Intensity of stimulation | Stimulation area | Measurement area | Task performed | Reported signals | Granular findings |
|---|---|---|---|---|---|---|---|---|---|
| Radel *et al* (2017) | Healthy | 22 | 20 min | 1.5 mA | Anode: AF4 and C2 Cathode: four placed at a distance of 40 mm around the anode | Right lateral prefrontal cortex and the right primary motor cortex | Fatiguing task | | • HD-tDCS had effect on the cognitive activation but no effects of stimulation were observed on endurance time or fatigue indices. |
| Muthalib *et al* (2016) | Healthy | 8 | 20 min | 2 mA | Left sensorimotor cortex | Bilateral sensorimotor cortex | Simple finger sequence | | • Online and offline anodal HD-tDCS reduced bilateral SMC activation |
| Hendy *et al* (2016) | Diseased | 42 | 20 min | 2 mA | Anode: left and right motor representation Cathode: right trapezius muscle | Prefrontal locations | Dual gait task | Trial protocol | • Lower limb strength, postural sway, gait speed and stride variability are improved by tDCS and progressive resistance training. |
| Takai *et al* (2016) | Healthy | 7 | 20 min | 1 mA | Bilateral M1 | SMA, left M1, and left primary sensory and motor cortex (S1) | Nil | Concentration changes in HbO | • Anodal and cathodal tDCS cause widespread changes in cerebral blood flow.<br>• The effect is not only observed under the electrodes but also in the other parts of the cortex. |
| Dutta *et al* (2015) | Diseased | 4 | 15 × 30 s | 0.5 mA | Anode: Cz Cathode: left supraorbital notch | Cz | Nil | Concentration changes in HbO, HbR, and EEG | • tDCS stimulation effected the phenomena of neurovascular coupling. |
| Yan *et al* (2015) | Healthy | 5 | 5 min | 1.5 mA | Left M1 area | Right M1 | | Concentration changes in HbO and connectivity | • Functional connectivity decreased during stimulation as compared to pre- and post-stimulation. |

(Continued.)

**Table 2.** (Continued.)

| Authors (year of publication) | Subject under observation | No. of subjects | Stimulation duration | Intensity of stimulation | Stimulation area | Measurement area | Task performed | Reported signals | Granular findings |
|---|---|---|---|---|---|---|---|---|---|
| Han *et al* (2014) | Rats | 7 | 10 min | 200 $\mu$A | Right barrel cortex area and the ventral thorax | Cover most part of the brain | | Concentration changes in HbO and HbR | • The HbO response increased during stimulation and decreased after it.<br>• Negative correlation was observed between HbO and HbR during stimulation period. |
| Khan *et al* (2013) | Healthy | 8 | 15 min | 2 mA | Bilateral M1 | Bilateral M1 | Wrist flexion task | Concentration changes in HbO and connectivity | • tDCS can alter inter-hemispheric balance and the laterality of cortical activity. |
| Muthalib *et al* (2013) | Healthy | 15 | 10 min | 2 mA | Left M1 area | Bilateral M1 | Maximal voluntary isometric contraction | Concentration changes in HbO and HbR | • Neuronal activation to maintain muscle force production was not modulated by anodal tDCS. |

and duration concerning the tDCS response. Early tDCS investigations employed intensities of up to 1 mA to alter corticospinal excitability in healthy persons (Yang *et al* 2021). Increasing tDCS intensity, on the other hand, does not always promote plasticity; instead, it may reverse the predicted direction of excitability change for the tested polarity (Batsikadze *et al* 2013). A thorough evaluation of anodal tDCS intensities between 0.5 and 2.0 mA in healthy people demonstrated no changes in corticospinal excitability regulation (Jamil *et al* 2017). Unexpectedly, only stimulation at 1 mA resulted in the predicted decrease of corticospinal excitability with cathodal tDCS. Although the ideal stimulation intensity is unknown, it appears that greater intensities (e.g. 2 mA) are not always more beneficial for anodal tDCS.

Similarly, the length of stimulation was expanded from 10 min in initial research to 20–30 min in subsequent investigations to improve therapeutic efficacy in patient groups (Nitsche *et al* 2003, Elsner *et al* 2016). However, there does not appear to be a direct link between increased duration and improved physiologic outcomes. In addition, after 18 min of continuous application of cathodal tDCS, the after-effects did not lead to any further excitement, and with a further increase in stimulation duration, there was no further improvement (Monte-Silva *et al* 2010). Monte-Silva *et al* (2013) claimed that prolonging the duration of anodal tDCS to twenty-six minutes reversed the excitation-to-suppression effects in the motor cortex. However, plasticity responses were longer-lasting when two thirteen-minute blocks of anodal tDCS were separated by twenty minutes of no stimulation. The intensity and duration of tDCS stimulation interact with neuronal responses. Greater than 1 mA stimulation increased corticospinal excitability regardless of stimulation time (i.e. less than or more than 10 min), but less than 1 mA stimulation increased corticospinal excitability if provided for more than 10 min (Dissanayaka *et al* 2017). Moreover, for example, twenty minutes of stimulation promoted plasticity, but thirty minutes had no impact (Vignaud *et al* 2018). Anodal tDCS with less than 1 mA intensity and ten minutes duration did not impact corticospinal excitability (Hordacre *et al* 2021). Plasticity after-effects are modulated by current density under the active electrode, although ideal parameters are unknown. Even though many current densities have been examined in healthy persons and patients, there is no consistent evidence supporting any one parameter.

No doubt, controlling the length of stimulation is complicated and dependent on several subject-specific characteristics. The duration of tDCS for a specific brain area was determined in a resting state study where a limiting mechanism for the stimulation duration of a diseased brain using functional connectivity and graph-theoretical parameters was proposed (Yaqub *et al* 2021). They examined the resting-state functional connectivity in the PFC after 10 min of HD-tDCS stimulation to see how it affected the right prefrontal cortex. The averaged HbO signal was used to build correlation maps that quantitatively quantify the resting-state functional connectivity after preprocessing the collected fNIRS data to eliminate noise from various sources. The findings revealed a high correlation between several combinations of channels that may be considered correlated. Based on the connectivity percentage across channels, the functional brain network for the entire PFC was partitioned into subnetworks. The independent short-range links of the right and left hemispheres containing connections within a hemisphere, long-range networks with links between the channels of the right and left hemispheres, and the whole PFC network including short- and long-range connections were investigated based on network theory properties. The results reveal that when the stimulation time is increased, the functional networks in the brain are enhanced. During the first 7 min, the region of interest improved brain state considerably. However, there was no discernible alteration in the brain state in the last 3 min of stimulation. Consequently, it is safe to conclude that the brain's gains were near saturation and that more stimulation should be avoided to limit overdosage. The proposed neurofeedback approach may be used to regulate the stimulus duration.

## 5. Open questions

Based on the literature, certain essential points need to be considered. These significant points include: (a) the number of participants required to conduct the study, (b) the exact brain region where stimulation has to be given, (c) the brain region that will be used as a reference during stimulation, (d) the polarity of the stimulation, (e) whether the study will be blinded, (f) the amount of current to be delivered to subjects, (g) how long stimulation will last, (h) how many brain stimulation sessions will be given, and (i) what will be the assessed variables. All these variables need addressing and be set as a benchmark for further studies. Some prominent methods that may act as breakthroughs in the field are discussed below.

### 5.1. Hybrid imaging-based approach

The excitable membranes of the brain tissue superpose the electric currents in the extracellular medium during neural stimulation and create a potential on the scalp (i.e. EEG). It has been shown that neuronal activity is closely linked to cerebral blood flow and the consequent supply of glucose via the neurovascular link, both spatially and temporally. On the other hand, fNIRS can capture hemodynamic responses, allowing continuous surveillance of cerebral oxygen and blood flow. The authors proposed the fusion of EEG and fNIRS data as a method for

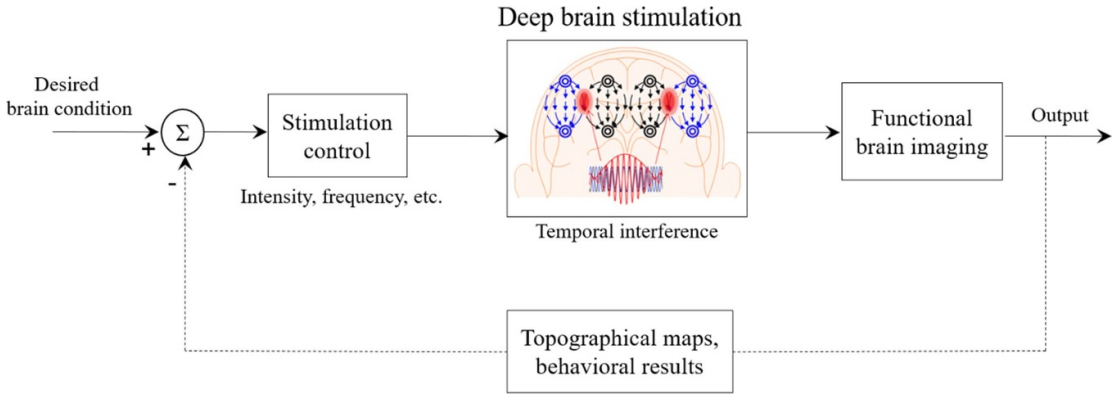


**Figure 7.** Proposed feedback control strategy for deep brain transcranial electrical stimulation.

more efficient online monitoring during stimulation. Multivariant machine learning methods (Shin *et al* 2018) can also be used to fuse multimodal neuroimaging functional data. For fNIRS, the individualized physical MRI model includes optical properties, such as the absorption and scattering coefficients of the various types of tissue, and explains the transport of photons through the tissues. Functional diffuse correlation spectroscopy and diffuse optical tomography extend fNIRS by overlapping high-density (Giovannella *et al* 2018, Yaqub *et al* 2020) measurements, which provides increased spatial precision in a three-dimensional perspective. For closed-loop control of multimodal imaging, connectivity needs to be analyzed in real-time for multi-channel tDCS in the source space (Yaqub *et al* 2018, 2021, Ghafoor *et al* 2022).

In future work, we propose using temporal interference for deep brain stimulation, as shown in figure 7 (Grossman *et al* 2017, 2018). Although techniques such as HD-tDCS have shown prominent results in cases of focal stimulation, deep brain stimulation may be the best option to achieve long-lasting effects. With the help of deep brain stimulation, the high risks of surgery can be avoided to reach the subcortical areas of the brain. In addition, one of the most prominent advantages of deep brain stimulation using tES is cost-efficiency. Further, the authors believe that targeted stimulation is possible with the help of deep brain stimulation, which might improve results. Alongside this, the design of a method to set a standard for the stimulation duration is a goal for the future. Instead of the hit-and-try method, the authors believe that specific criteria for selecting the best suitable stimulation duration are a need of the era that will be addressed in future studies.

### 5.2. Issues concerning artifact removal

When captured during tACS, the EEG signal is polluted by a substantial electrical disturbance. However, this setup is sufficient to show that tACS is responsible for developing brain oscillations explicitly. The reduction of artifacts is necessary for the online analysis of the effects of tACS. The perfect solution is to distinguish between artifacts and physiological signals. Each of the oscillations (or harmonics) should be analyzed at the frequency of the stimulation. With these approaches, one key question remains unanswered: Can a small remaining entity from entrained brain activity be discerned reliably based mainly on EEG data? It is also difficult to evaluate online neural responses at the same frequency using tACS stimulation (e.g. increases in alpha oscillations during 10 Hz tACS stimulation). Studies should target frequencies far from the frequency of stimulation and its harmonics.

In humans, the EEG records of the frequency band 1–15 Hz are influenced by cardiac activity and the blinking of the eye (Gebodh *et al* 2017, Noury and Siegel 2017). This effect is most pronounced in the frontal areas. In addition, the subject's movement should be avoided, and stimulation electrodes should be carefully placed so that they do not move. The issue of motion artifact can be catered to by using fNIRS as a brain-imaging modality. As fNIRS is less susceptible to motion artifacts than EEG, it provides an avenue to avoid motion artifacts in the first place. Also, the advantage of fNIRS over EEG is that there is no interference between tES and fNIRS signals, which is not the case in EEG. Usually, the EEG analyses are performed before and after the stimulation period, as the supplied current during the stimulation period causes significant noise in the measured EEG signals. However, fNIRS is free from this issue as it is not subjected to optoelectrical interference.

### 5.3. Repetitive stimulation

The discovery of increased tDCS effectiveness with repeated stimulation over days is significant in neurorehabilitation. The effects of repetitive tACS have also been briefly explored by (Hsu *et al* 2019), who showed that tACS with a 1 min intersession interval (i.e. duration of two adjacent tACS) improved multitasking performance. Therefore, repeated daily

stimulation will prove to be the most effective stimulation protocol in the foreseeable future. The value of the stimulation interval has not yet been illustrated. This issue is of significant concern and needs to be addressed in future studies. One way to achieve this is with the implementation of modern machine learning techniques to estimate the amount of stimulation to be delivered depending on person (Hong *et al* 2018, Ahamdipour *et al* 2021, Benrabah *et al* 2021, Xu *et al* 2021a, 2021b). Furthermore, the specific areas that result in the best cognitive improvements when stimulated must be determined.

### 5.4. Safety and tolerability

tDCS at 1 mA requires larger electrodes than those used for EEG to prevent skin burns. The experiments were painful for subjects when the applied current reached 3 mA (Furubayashi *et al* 2008). It can also be interpreted as a natural security defense against higher strength stimulation, although animal studies show the method itself is considered secure (Liebetanz *et al* 2009). Additional parameters have been used to enhance physiological comparability and protection criteria. A recent comparative study (Ghafoor *et al* 2022) of tACS/tDCS with fNIRS concluded the following: (a) there were no severe adverse effects in either scenario of stimulation (tDCS or tACS), (b) except for fatigue and tingling, no difference was seen in between-stimulation condition comparisons for any adverse effect, (c) tingling was statistically higher in tACS than in tDCS, (d) the tACS group had more fatigue than the tDCS group. Moreover, practically everyone in the tACS group experienced moderate to severe phosphene and bumping symptoms. This effect might be caused by the stimulation/return electrodes in the PFC being so close to the eyes. Participants in the tDCS group, on the other hand, reported no phosphene impact.

## 6. Conclusion

After providing an overview of what has been achieved in the field of fNIRS-tES, it can be concluded that a meticulous and refined understanding of the physiological response to tES will enhance the experimental protocols for experiments based on neurostimulation. This will aid in the production of substantially consistent results. For future studies, another open question that needs attention is whether the electric field attenuated by tES that reaches the human brain directly affects neuronal networks. The authors believe that the tES approaches will contribute to significant advances in human neuroscience. In addition, the permanence of the effects generated by these experiments should be determined. Once the optimal stimulation duration for tES is decided and a suitable paradigm is developed, tES and fNIRS will aid in developing complete theories regarding brain networks and functions.

## Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

## Acknowledgment

This work was supported by the Technology Innovation Program (Grant No. 20016846, Development of fNIRS-based multimonitoring healthcare device for sleep state diagnosis) funded by the Ministry of Trade, Industry & Energy (MOTIE, Korea).

## ORCID iDs

Keum-Shik Hong https://orcid.org/0000-0002-8528-4457
M N Afzal Khan https://orcid.org/0000-0003-2498-449X
Usman Ghafoor https://orcid.org/0000-0001-5464-4002

## References

Ahmadipour P, Yang Y, Chang E F and Shanechi M M 2021 Adaptive tracking of human ECoG network dynamics *J. Neural Eng.* **18** 016011

Alizadehgoradel J, Imani S, Nejati V, Vanderhasselt M A, Molaei B, Salehinejad M A, Ahmadi S and Taherifard M 2021 Improved executive functions and reduced craving in youths with methamphetamine addiction: evidence from combined transcranial direct current stimulation with mindfulness treatment *Clin. Psychopharmacol. Neurosci.* **19** 653

Alizadehgoradel J, Nejati V, Movahed F S, Imani S, Taherifard M, Mosayebi-Samani M, Vicario C M, Nitsche M A and Salehinejad M A 2020 Repeated stimulation of the dorsolateral-prefrontal cortex improves executive dysfunctions and craving in drug addiction: a randomized, double-blind, parallel-group study *Brain Stimul.* **13** 582–93

Andrade S M, Marcolino A S, Ponce C T, de Aquino Gouveia M L, Martins W K and de Oliveira E A 2018 Transcranial direct current stimulation and physiotherapy in the treatment of fibromyalgia: case series *Acta Sci. Health Sci.* **40** 35240

Antal A, Boros K, Poreisz C, Chaieb L, Terney D and Paulus W 2008 Comparatively weak after-effects of transcranial alternating current stimulation (tACS) on cortical excitability in humans *Brain Stimul.* **1** 97–105

Antal A and Herrmann C S 2016 Transcranial alternating current and random noise stimulation: possible mechanisms *Neural Plast.* **2016** 3616807

Arroyo-Fernández R, Avendaño-Coy J, Velasco-Velasco R, Palomo-Carrión R, Bravo-Esteban E and Ferri-Morales A 2021 A new approach to assess blinding for transcranial direct current stimulation treatment in patients with fibromyalgia. A randomized clinical trial *Brain Sci.* **11** 1335

Batsikadze G, Moliadze V, Paulus W, Kuo M and Nitsche M A 2013 Partially non-linear stimulation intensity-dependent effects of direct current stimulation on motor cortex excitability in humans *J. Physiol.* **591** 1987–2000

Bennett J D, John S E, Grayden D B and Burkitt A N 2021 A neurophysiological approach to spatial filter selection for adaptive brain–computer interfaces *J. Neural Eng.* **18** 026017

Benrabah M, Kara K, AitSahed O and Hadjili M L 2021 Adaptive Fourier series neural network PID controller *Int. J. Control Autom. Syst.* **19** 3388–99

Beretta V S, Vitório R, Nóbrega-Sousa P, Conceição N R, Orcioli-Silva D, Pereira M P and Gobbi L T B 2020 Effect of different intensities of transcranial direct current stimulation on postural response to external perturbation in patients with Parkinson's disease *Neurorehabil. Neural Repair* **34** 1009–19

Berger A, Pixa N H, Steinberg F and Doppelmayr M 2018 Brain oscillatory and hemodynamic activity in a bimanual coordination task following transcranial alternating current stimulation (tACS): a combined EEG-fNIRS study *Front. Behav. Neurosci.* **12** 67

Berglund-Barraza A, Tian F, Basak C, Hart J and Evans J L 2020 Tracking changes in frontal lobe hemodynamic response in individual adults with developmental language disorder following HD tDCS enhanced phonological working memory training: an fNIRS feasibility study *Front. Hum. Neurosci.* **14** 362

Berryhill M E and Martin D 2018 Cognitive effects of transcranial direct current stimulation in healthy and clinical populations: an overview *J. ECT* **34** e25–35

Besson P, Muthalib M, Dray G, Rothwell J and Perrey S 2019 Concurrent anodal transcranial direct-current stimulation and motor task to influence sensorimotor cortex activation *Brain Res.* **1710** 181–7

Borragán G, Gilson M, Guerrero-Mosquera C, Di Ricci E, Slama H and Peigneux P 2018 Transcranial direct current stimulation does not counteract cognitive fatigue, but induces sleepiness and an inter-hemispheric shift in brain oxygenation *Front. Psychol.* **9** 2351

Cao J, Liu H and Alexandrakis G 2018b Modulating the resting-state functional connectivity patterns of language processing areas in the human brain with anodal transcranial direct current stimulation applied over the Broca's area *Neurophotonics* **5** 025002

Cao J, Wang X, Liu H and Alexandrakis G 2018a Directional changes in information flow between human brain cortical regions after application of anodal transcranial direct current stimulation (tDCS) over Broca's area *Biomed. Opt. Express* **9** 5296–317

Cappon D, D'Ostilio K, Garraux G, Rothwell J and Bisiacchi P 2016a Effects of 10 Hz and 20 Hz transcranial alternating current stimulation on automatic motor control *Brain Stimul.* **9** 518–24

Cappon D, Jahanshahi M and Bisiacchi P 2016b Value and efficacy of transcranial direct current stimulation in the cognitive rehabilitation: a critical review since 2000 *Front. Neurosci.* **10** 157

Cattagni T, Geiger M, Supiot A, de Mazancourt P, Pradon D, Zory R and Roche N 2019 A single session of anodal transcranial direct current stimulation applied over the affected primary motor cortex does not alter gait parameters in chronic stroke survivors *Neurophysiol. Clin.* **49** 283–93

Chander B S, Witkowski M, Braun C, Robinson S E, Born J, Cohen L G, Birbaumer N and Soekadar S R 2016 tACS phase locking of frontal midline theta oscillations disrupts working memory performance *Front. Cell Neurosci.* **10** 120

Chari A, Hentall I D, Papadopoulos M C and Pereira E A C 2017 Surgical neurostimulation for spinal cord injury *Brain Sci.* **7** 18

Chenot Q, Hamery C, Lepron E, Besson P, De Boissezon X, Perrey S and Scannella S 2022 Performance after training in a complex cognitive task is enhanced by high-definition transcranial random noise stimulation *Sci. Rep.* **12** 4618

Choe J, Coffman B A, Bergstedt D T, Ziegler M D and Phillips M E 2016 Transcranial direct current stimulation modulates neuronal activity and learning in pilot training *Front. Hum. Neurosci.* **10** 34

Clark D J, Chatterjee S A, Skinner J W, Lysne P E, Sumonthee C, Wu S S, Cohen R A, Rose D K and Woods A J 2020 Combining frontal transcranial direct current stimulation with walking rehabilitation to enhance mobility and executive function: a pilot clinical trial *Neuromodulation* **24** 950–59

Conceição N R, Gobbi L T B, Nóbrega-Sousa P, Orcioli-Silva D, Beretta V S, Lirani-Silva E, Okano A H and Vitório R 2021 Aerobic exercise combined with transcranial direct current stimulation over the prefrontal cortex in Parkinson disease: effects on cortical activity, gait, and cognition *Neurorehabil. Neural Repair* **35** 717–28

Cortes M, Medeiros A H, Gandhi A, Lee P, Krebs H I, Thickbroom G, Edwards D and Krebs H I 2017 Improved grasp function with transcranial direct current stimulation in chronic spinal cord injury *NeuroRehabilitation* **41** 51–59

Di Rosa E, Brigadoi S, Cutini S, Tarantino V, Dell'Acqua R, Mapelli D, Braver T S and Vallesi A 2019 Reward motivation and neurostimulation interact to improve working memory performance in healthy older adults: a simultaneous tDCS-fNIRS study *Neuroimage* **202** 116062

Dissanayaka T, Zoghi M, Farrell M, Egan G F and Jaberzadeh S 2017 Does transcranial electrical stimulation enhance corticospinal excitability of the motor cortex in healthy individuals? A systematic review and meta-analysis *Eur J Neurosci* **46** 1968–90

Doost M Y *et al* 2019 Learning a bimanual cooperative skill in chronic stroke under noninvasive brain stimulation: a randomized controlled trial *Neurorehabil. Neural Repair* **33** 486–98

Dubuson M *et al* 2021 Transcranial direct current stimulation combined with alcohol cue inhibitory control training reduces the risk of early alcohol relapse: a randomized placebo-controlled clinical trial *Brain Stimul.* **14** 1531–43

Dutta A, Jacob A, Chowdhury S R, Das A and Nitsche M A 2015 EEG-NIRS based assessment of neurovascular coupling during anodal transcranial direct current stimulation—a stroke case series *J. Med. Syst.* **39** 205

Ehlis C, Haeussinger F B, Gastel A, Fallgatter A J and Plewnia C 2016 Task-dependent and polarity-specific effects of prefrontal transcranial direct current stimulation on cortical activation during word fluency *Neuroimage* **140** 134–40

Elsner B, Kugler J, Pohl M and Mehrholz J 2016 Transcranial direct current stimulation (tDCS) for improving activities of daily living, and physical and cognitive functioning, in people after stroke *Cochrane Database Syst. Rev.* **3** Cd009645

Eskandari Z, Dadashi M, Mostafavi H, Kia A A and Pirzeh R 2019 Comparing the efficacy of anodal, cathodal, and sham transcranial direct current stimulation on brain-derived neurotrophic factor and psychological symptoms in opioid-addicted patients *Basic Clin. Neurosci.* **10** 641

Esmaeilpour Z, Shereen A D, Ghobadi-Azbari P, Datta A, Woods A J, Ironside M, O'Shea J, Kirk U, Bikson M and Ekhtiari H 2020 Methodology for tDCS integration with fMRI *Hum. Brain Mapp.* **41** 1950–67

Feil S *et al* 2019 Left shifting of language related activity induced by bihemispheric tDCS in postacute aphasia following stroke *Front. Neurosci.* **13** 295

Feurra M, Paulus W, Walsh V and Kanai R 2011 Frequency specific modulation of human somatosensory cortex *Front. Psychol.* **2** 13

Figeys M, Zeeman M and Kim E S 2021 Effects of transcranial direct current stimulation (tDCS) on cognitive performance and cerebral oxygen hemodynamics: a systematic review *Front. Hum. Neurosci.* **15** 623315

Fregni F *et al* 2005 Transcranial direct current stimulation of the unaffected hemisphere in stroke patients *Neuroreport* **16** 1551–5

Fregni F *et al* 2021 Evidence-based guidelines and secondary meta-analysis for the use of transcranial direct current stimulation in neurological and psychiatric disorders *Int. J. Neuropsychopharmacol.* **24** 256–313

Fricová J, Englerová K, Nedvídek J and Rokyta R 2019 The treatment of orofacial pain by using transcranial direct current stimulation *Physiol. Res.* **68** S367–72

Fröhlich F, Sellers K K and Cordle A L 2015 Targeting the neurophysiology of cognitive systems with transcranial

alternating current stimulation *Expert Rev. Neurother.* **15** 145–67
Furubayashi T, Terao Y, Arai N, Okabe S, Mochizuki H, Hanajima R, Hamada M, Yugeta A, Inomata-Terada S and Ugawa Y 2008 Short and long duration transcranial direct current stimulation (tDCS) over the human hand motor area *Exp. Brain Res.* **185** 279–86
Gao Y *et al* 2021 Decreasing the surgical errors by neurostimulation of primary motor cortex and the associated brain activation via neuroimaging *Front. Neurosci.* **15** 265
Gaudreault P O *et al* 2021 A double-blind sham-controlled phase 1 clinical trial of tDCS of the dorsolateral prefrontal cortex in cocaine inpatients: craving, sleepiness, and contemplation to change *Eur. J. Neurosci.* **53** 3212–30
Gebodh N, Adair D, Chelette K, Esmaeilpour Z, Bikson M and Dmochowski J 2017 Physiologic artifacts when combining EEG and tDCS *Brain Stimul.* **10** e33
Ghafoor U, Lee J H, Hong K S, Park S S, Kim J and Yoo H R 2019 Effects of acupuncture therapy on MCI patients using functional near-infrared spectroscopy *Front. Aging Neurosci.* **11** 237
Ghafoor U, Yang D and Hong K-S 2022 Neuromodulatory effects of HD-tACS/tDCS on the prefrontal cortex: a resting-state fNIRS-EEG study *IEEE J. Biomed. Health Inf.* **26** 2192–203
Giovannella M, Ibañez D, Gregori-Pla C, Kacprzak M, Mitjà G, Ruffini G and Durduran T 2018 Concurrent measurement of cerebral hemodynamics and electroencephalography during transcranial direct current stimulation *Neurophotonics* **5** 015001
Gözenman F and Berryhill M E 2016 Working memory capacity differentially influences responses to tDCS and HD-tDCS in a retro-cue task *Neurosci. Lett.* **629** 105–9
Grossman N *et al* 2017 Noninvasive deep brain stimulation via temporally interfering electric fields *Cell* **169** 1029–41
Grossman N, Okun M S and Boyden E S 2018 Translating temporal interference brain stimulation to treat neurological and psychiatric conditions *JAMA Neurol.* **75** 1307–8
Hallett M 2000 Transcranial magnetic stimulation and the human brain *Nature* **406** 147–50
Han C H, Song H, Kang Y G, Kim B M and Im C H 2014 Hemodynamic responses in rat brain during transcranial direct current stimulation: a functional near-infrared spectroscopy study *Biomed. Opt. Express* **5** 1812–21
Harris D M, Rantalainen T, Muthalib M, Johnson L, Duckham R L, Smith S T, Daly R M and Teo W P 2018 Concurrent exergaming and transcranial direct current stimulation to improve balance in people with Parkinson's disease: study protocol for a randomised controlled trial *Trials* **19** 387
Helfrich R F, Schneider T R, Rach S, Trautmann-Lengsfeld S A, Engel A K and Herrmann C S 2014 Entrainment of brain oscillations by transcranial alternating current stimulation *Curr. Biol.* **24** 333–9
Hendy A M, Tillman A, Rantalainen T, Muthalib M, Johnson L, Kidgell D J, Wundersitz D, Enticott P G and Teo W P 2016 Concurrent transcranial direct current stimulation and progressive resistance training in Parkinson's disease: study protocol for a randomised controlled trial *Trials* **17** 326
Herrmann C S, Rach S, Neuling T and Struber D 2013 Transcranial alternating current stimulation: a review of the underlying mechanisms and modulation of cognitive processes *Front. Hum. Neurosci.* **7** 279
Herrmann M J, Horst A K, Löble S, Möll M T, Katzorke A and Polak T 2017 Relevance of dorsolateral and frontotemporal cortex on the phonemic verbal fluency—a fNIRS-study *Neuroscience* **367** 169–77
Hofer A-S and Schwab M E 2019 Enhancing rehabilitation and functional recovery after brain and spinal cord trauma with electrical neuromodulation *Curr. Opin. Neurol.* **32** 828–35
Holla B, Biswal J, Ramesh V, Shivakumar V, Bharath R D, Benegal V, Venkatasubramanian G, Chand P K and Murthy P 2020 Effect of prefrontal tDCS on resting brain fMRI graph measures in alcohol use disorders: a randomized, double-blind, sham-controlled study *Prog. Neuropsychopharmacol. Biol. Psychiatry* **102** 109950
Hong K S, Aziz N and Ghafoor U 2018 Motor-commands decoding using peripheral nerve signals: a review *J. Neural Eng.* **15** 031004
Hong K S, Ghafoor U and Khan M J 2020 Brain-machine interfaces using functional near-infrared spectroscopy: a review *Artif. Life Robot.* **25** 204–18
Hong K-S and Yaqub M A 2019 Application of functional near-infrared spectroscopy in the health industry: a review *J. Innov. Opt. Health Sci.* **12** 1930012
Hordacre B, McCambridge A B, Ridding M C and Bradnam L V 2021 Can transcranial direct current stimulation enhance poststroke motor recovery?: Development of a theoretical patient-tailored model *Neurology* **97** 170–80
Horvath J C, Forte J D and Carter O 2015 Evidence that transcranial direct current stimulation (tDCS) generates little-to-no reliable neurophysiologic effect beyond MEP amplitude modulation in healthy human subjects: a systematic review *Neuropsychologia* **66** 213–36
Hsu W-Y, Zanto T P and Gazzaley A 2019 Parametric effects of transcranial alternating current stimulation on multitasking performance *Brain Stimul.* **12** 73–83
Hummel F, Celnik P, Giraux P, Floel A, Wu W, Gerloff C and Cohen L G 2005 Effects of non-invasive cortical stimulation on skilled motor function in chronic stroke *Brain* **128** 490–9
Iannone A, Allam N and Brasil-Neto J P 2019 Safety of transcranial direct current stimulation in a patient with deep brain stimulation electrodes *Arq. Neuropsiquiatr.* **77** 174–8
Ikeda Y, Kikuchi M, Noguchi-Shinohara M, Iwasa K, Kameya M, Hirosawa T, Yoshita M, Ono K, Samuraki-Yokohama M and Yamada M 2020 Spontaneous MEG activity of the cerebral cortex during eyes closed and open discriminates Alzheimer's disease from cognitively normal older adults *Sci. Rep.* **10** 9132
Jamil A, Batsikadze G, Kuo H-I, Labruna L, Hasan A, Paulus W and Nitsche M A 2017 Systematic evaluation of the impact of stimulation intensity on neuroplastic after-effects induced by transcranial direct current stimulation *J. Physiol.* **595** 1273–88
Jones K T, Gözenman F and Berryhill M E 2015 The strategy and motivational influences on the beneficial effect of neurostimulation: a tDCS and fNIRS study *Neuroimage* **105** 238–47
Kang J H, Choi S E, Park D J, Xu H, Lee J K and Lee S S 2020 Effects of add-on transcranial direct current stimulation on pain in Korean patients with fibromyalgia *Sci. Rep.* **10** 1
Karabanov A, Ziemann U, Hamada M, George M S, Quartarone A, Classen J, Massimini M, Rothwell J and Siebner H R 2015 Consensus paper: probing homeostatic plasticity of human cortex with non-invasive transcranial brain stimulation *Brain Stimul.* **8** 442–54
Kasschau M, Reisner J, Sherman K, Bikson M, Datta A and Charvet L E 2016 Transcranial direct current stimulation is feasible for remotely supervised home delivery in multiple sclerosis *Neuromodulation* **19** 824–31
Kasten F H and Herrmann C S 2017 Transcranial alternating current stimulation (tACS) enhances mental rotation performance during and after stimulation *Front. Hum. Neurosci.* **11** 2
Khan B, Hodics T, Hervey N, Kondraske G, Stowe A M and Alexandrakis G 2013 Functional near-infrared spectroscopy maps cortical plasticity underlying altered motor performance induced by transcranial direct current stimulation *J. Biomed. Opt.* **18** 116003
Khan M N A, Bhutta M R and Hong K-S 2020 Task-specific stimulation duration for fNIRS brain-computer interface *IEEE Access* **8** 89093–105
Khan M N A, Ghafoor U, Yoo H-R and Hong K-S 2022 Acupuncture enhances brain function in patients with mild cognitive impairment: evidence from a functional-near infrared spectroscopy study *Neural Regen. Res.* **17** 1850–6

Khan M N A and Hong K-S 2021 Most favorable stimulation duration in the sensorimotor cortex for fNIRS-based BCI *Biomed. Opt. Express* **12** 5939–54

Kindred J H, Kautz S A, Wonsetler E C and Bowden M G 2019 Single sessions of high-definition transcranial direct current stimulation do not alter lower extremity biomechanical or corticomotor response variables post-stroke *Front. Neurosci.* **13** 286

Kroczek A M, Häußinger F B, Rohe T, Schneider S, Plewnia C, Batra A, Fallgatter A J and Ehlis A C 2016 Effects of transcranial direct current stimulation on craving, heart-rate variability and prefrontal hemodynamics during smoking cue exposure *Drug Alcohol Depend.* **168** 123–7

Kumru H, Flores A, Rodriguez-Canon M, Soriano I, Garcia L and Vidal-Samso J 2020 Non-invasive brain and spinal cord stimulation for motor and functional recovery after a spinal cord injury *Rev. Neurol.* **70** 461–77

Kuo M F and Nitsche M A 2015 Exploring prefrontal cortex functions in healthy humans by transcranial electrical stimulation *Neurosci. Bull.* **31** 198–206

Lang J, Sances A and Larson S J 1969 Determination of specific cerebral impedance and cerebral current density during the application of diffuse electrical currents *Med. Biol. Eng.* **7** 517–26

Legrand N, Etard O, Vandevelde A, Pierre M, Viader F, Clochon P, Doidy F, Peschanski D, Eustache F and Gagnepain P 2020 Long-term modulation of cardiac activity induced by inhibitory control over emotional memories *Sci. Rep.* **10** 15008

Li H, Zhu N, Klomparens E A, Xu S, Wang M, Wang Q, Wang J and Song L 2019 Application of functional near-infrared spectroscopy to explore the neural mechanism of transcranial direct current stimulation for post-stroke depression *Neurol. Res.* **41** 714–21

Liebetanz D, Koch R, Mayenfels S, Konig F, Paulus W and Nitsche M A 2009 Safety limits of cathodal transcranial direct current stimulation in rats *Clin. Neurophysiol.* **120** 1161–7

Liu A, Fregni F, Hummel F and Pascual-Leone A 2012 *Transcranial Brain Stimulation* ed C Miniussi, W Paulus and P M Rossini (Boca Raton, FL: CRC Press) pp 359–414

Lu H, Gong Y, Huang P, Zhang Y, Guo Z, Zhu X and You X 2021 Effect of repeated anodal HD-tDCS on executive functions: evidence from a pilot and single-blinded fNIRS study *Front. Hum. Neurosci.* **14** 609

Malandain L, Blanc J V, Ferreri F, Giorgiadis T, Mosser S, Mouchabac S and Thibaut F 2020 First case report of tDCS efficacy in severe chemsex addiction *Dialogues Clin. Neurosci.* **22** 295

Martinotti G *et al* 2019 Transcranial direct current stimulation reduces craving in substance use disorders: a double-blind, placebo-controlled study *J. ECT* **35** 207–11

Matias M G, Maciel D G, França I M, Cerqueira M S, Silva T C, Okano A H, Pegado R and Vieira W H B 2022 Transcranial direct current stimulation associated with functional exercise program for treating fibromyalgia: a randomized controlled trial *Arch. Phys. Med. Rehabil.* **103** 245–54

Mazzoleni S, Tran V D, Dario P and Posteraro F 2019 Effects of transcranial direct current stimulation (tDCS) combined with wrist robot-assisted rehabilitation on motor recovery in subacute stroke patients: a randomized controlled trial *IEEE Trans. Neural. Syst. Rehabil. Eng.* **27** 1458–66

McKendrick R, Falcone B, Scheldrup M and Ayaz H 2020 Effects of transcranial direct current stimulation on baseline and slope of prefrontal cortex hemodynamics during a spatial working memory task *Front. Hum. Neurosci.* **14** 64

Meiron O, Gale R, Namestnic J, Bennet-Back O, Gebodh N, Esmaeilpour Z, Mandzhiyev V and Bikson M 2019 Antiepileptic effects of a novel non-invasive neuromodulation treatment in a subject with early-onset epileptic encephalopathy: case report with 20 sessions of HD-tDCS intervention *Front. Neurosci.* **13** 547

Merzagora A C, Foffani G, Panyavin I, Mordillo-Mateos L, Aguilar J, Onaral B and Oliviero A 2010 Prefrontal hemodynamic changes produced by anodal direct current stimulation *Neuroimage* **49** 2304–10

Monte-Silva K K, Kuo M F, Liebetanz D, Paulus W and Nitsche M A 2010 Shaping the optimal repetition interval for cathodal transcranial direct current stimulation (tDCS) *J. Neurophysiol.* **103** 1735–40

Monte-Silva K, Kuo M-F, Hessenthaler S, Fresnoza S, Liebetanz D, Paulus W and Nitsche M A 2013 Induction of late LTP-like plasticity in the human motor cortex by repeated non-invasive brain stimulation *Brain Stimul.* **6** 424–32

Muthalib M, Besson P, Rothwell J and Perrey S 2018 Focal hemodynamic responses in the stimulated hemisphere during high-definition transcranial direct current stimulation *Neuromodulation* **21** 348–54

Muthalib M, Besson P, Rothwell J, Ward T and Perrey S 2016 Effects of anodal high-definition transcranial direct current stimulation on bilateral sensorimotor cortex activation during sequential finger movements: an fNIRS study *Adv. Exp. Med. Biol.* **876** 351–9

Muthalib M, Kan B, Nosaka K and Perrey S 2013 Effects of transcranial direct current stimulation of the motor cortex on prefrontal cortex activation during a neuromuscular fatigue task: an fNIRS study *Adv. Exp. Med. Biol.* **789** 73–79

Narita Z, Noda T, Setoyama S, Sueyoshi K, Inagawa T and Sumiyoshi T 2018 The effect of transcranial direct current stimulation on psychotic symptoms of schizophrenia is associated with oxy-hemoglobin concentrations in the brain as measured by near-infrared spectroscopy: a pilot study *J. Psychiatr. Res.* **103** 5–9

Nicolas-Alonso L F and Gomez-Gil J 2012 Brain–computer interfaces, a review *Sensors* **12** 1211–79

Nitsche M A, Fricke K, Henschke U, Schlitterlau A, Liebetanz D, Lang N, Henning S, Tergau F and Paulus W 2003 Pharmacological Modulation of Cortical Excitability Shifts Induced by Transcranial Direct Current Stimulation in Humans *J. Physiol.* **553** 293–301

Nitsche M A and Paulus W 2000 Excitability changes induced in the human motor cortex by weak transcranial direct current stimulation *J. Physiol.* **527** 633–9

Nitsche M A and Paulus W 2001 Sustained excitability elevations induced by transcranial DC motor cortex stimulation in humans *Neurology* **57** 1899–901

Noury N and Siegel M 2017 Phase properties of transcranial electrical stimulation artifacts in electrophysiological recordings *Neuroimage* **158** 406–16

Oh D C and Jo Y U 2021 Classification of hand gestures based on multi-channel EMG by scale average wavelet transform and convolutional neural network *Int. J. Control Autom. Syst.* **19** 1443–50

Orcioli-Silva D, Islam A, Baker M R, Gobbi L T B, Rochester L and Pantall A 2021 Bi-anodal transcranial direct current stimulation combined with treadmill walking decreases motor cortical activity in young and older adults *Front. Aging Neurosci.* **13** 739998

Patel R, Dawidziuk A, Darzi A W, Singh H and Leff D R 2020 Systematic review of combined functional near-infrared spectroscopy and transcranial direct-current stimulation studies *Neurophotonics* **7** 020901

Pedron S, Dumontoy S, González-Marín M D C, Coune F, Van Schuerbeek A, Haffen E, Naassila M and Van Waes V 2022 Transcranial direct current stimulation (tDCS) reduces motivation to drink ethanol and reacquisition of ethanol self-administration in female mice *Sci. Rep.* **12** 198

Perri R L and Perrotta D 2021 Transcranial direct current stimulation of the prefrontal cortex reduces cigarette craving in not motivated to quit smokers: a randomized, sham-controlled study *Addict. Behav.* **120** 106956

Petrosyan A, Sinkin M, Lebedev M and Ossadtchi A 2021 Decoding and interpreting cortical signals with a compact convolutional neural network *J. Neural Eng.* **18** 026019

Polanía R, Nitsche M A and Ruff C C 2018 Studying and modifying brain function with non-invasive brain stimulation *Nat. Neurosci.* **21** 174–87

Pollonini L, Miao H and Ahn H 2020a Longitudinal effect of transcranial direct current stimulation on knee osteoarthritis patients measured by functional infrared spectroscopy: a pilot study *Neurophotonics* **7** 025004

Pollonini L, Montero-Hernandez S, Park L, Miao H, Mathis K and Ahn H 2020b Functional near-infrared spectroscopy to assess central pain responses in a nonpharmacologic treatment trial of osteoarthritis *J. Neuroimaging* **30** 808–14

Prehn K and Flöel A 2015 Potentials and limits to enhance cognitive functions in healthy and pathological aging by tDCS *Front. Cell Neurosci.* **9** 355

Radel R, Tempest G, Denis G, Besson P and Zory R 2017 Extending the limits of force endurance: stimulation of the motor or the frontal cortex? *Cortex* **97** 96–108

Salatino A, Miccolis R, Gammeri R, Ninghetto M, Belli F, Nobili M, Mouraux A and Ricci R 2021 Improvement of impulsivity and decision making by transcranial direct current stimulation of the dorsolateral prefrontal cortex in a patient with gambling disorder *J. Gambl. Stud.* **38** 627–34

Santos V S D S D *et al* 2018 Cognitive effects of transcranial direct current stimulation combined with working memory training in fibromyalgia: a randomized clinical trial *Sci. Rep.* **8** 12477

Sattar N Y, Kausar Z, Usama S A, Farooq U and Khan U S 2021 EMG based control of transhumeral prosthesis using machine learning algorithms *Int. J. Control Autom. Syst.* **19** 3522–32

Schommartz I, Dix A, Passow S and Li S C 2021 Functional effects of bilateral dorsolateral prefrontal cortex modulation during sequential decision-making: a functional near-infrared spectroscopy study with offline transcranial direct current stimulation *Front. Hum. Neurosci.* **14** 605190

Shin J, Von Lühmann A, Kim D W, Mehnert J, Hwang H J and Müller K R 2018 Simultaneous acquisition of EEG and NIRS during cognitive tasks for an open access dataset *Sci. Data* **5** 180003

Sood M, Besson P, Muthalib M, Jindal U, Perrey S, Dutta A and Hayashibe M 2016 NIRS-EEG joint imaging during transcranial direct current stimulation: online parameter estimation with an autoregressive model *J. Neurosci. Methods* **274** 71–80

Stagg C J and Nitsche M A 2011 Physiological basis of transcranial direct current stimulation *Neuroscientist* **17** 37–53

Stephens J A and Berryhill M E 2016 Older adults improve on everyday tasks after working memory training and neurostimulation *Brain Stimul.* **9** 553–9

Takai H, Tsubaki A, Sugawara K, Miyaguchi S, Oyanagi K, Matsumoto T, Onishi H and Yamamoto N 2016 Effect of transcranial direct current stimulation over the primary motor cortex on cerebral blood flow: a time course study using near-infrared spectroscopy *Adv. Exp. Med. Biol.* **876** 335–41

Tian Y, Ma L, Xu W and Chen S F 2020 The influence of listening to music on adults with left-behind experience revealed by EEG-based connectivity *Sci. Rep.* **10** 7575

Toleikis J R, Sances A Jr. and Larson S J 1974 Effects of diffuse transcerebral electrical currents on cortical unit potential activity *Anesth. Analg.* **53** 48–55

Verma R, Jha A and Singh S 2019 Functional near-infrared spectroscopy to probe tDCS -induced cortical functioning changes in tinnitus *J. Int. Adv. Otol.* **15** 321–5

Verveer I, Remmerswaal D, van Der Veen F M and Franken I H 2020 Long-term tDCS effects on neurophysiological measures of cognitive control in tobacco smokers *Biol. Psychol.* **156** 107962

Vignaud P, Mondino M, Poulet E, Palm U and Brunelin J 2018 Duration but not intensity influences transcranial direct current stimulation (tDCS) after-effects on cortical excitability *Neurophysiol. Clin. Neurophysiol.* **48** 89–92

Vogeti S, Boetzel C and Herrmann C S 2022 Entrainment and spike-timing dependent plasticity–a review of proposed mechanisms of transcranial alternating current stimulation *Front. Syst. Neurosci.* **16** 827353

Vosskuhl J, Struber D and Herrmann C S 2015 Transkranielle wechselstromstimulation. Entrainment und funktionssteuerung neuronaler netzwerke [Transcranial alternating current stimulation. Entrainment and function control of neuronal networks] *Nervenarzt* **86** 1516–22

Wang S M S, Huang Y J, Chen J J J, Wu C W, Chen C A, Lin C W, Nguyen V T and Peng C W 2021 Designing and pilot testing a novel high-definition transcranial burst electrostimulation device for neurorehabilitation *J. Neural Eng.* **18** 056030

Wessel M J, Zimerman M and Hummel F C 2015 Non-invasive brain stimulation: an interventional tool for enhancing behavioral training after stroke *Front. Hum. Neurosci.* **9** 265

Woods A J *et al* 2016 A technical guide to tDCS, and related non-invasive brain stimulation tools *Clin. Neurophysiol.* **127** 1031–48

Xie H, Wu B L and Liu W X 2021 Adaptive neural network model-based event-triggered attitude tracking control for spacecraft *Int. J. Control Autom. Syst.* **19** 172–85

Xu L, Xu M, Ma Z, Wang K, Jung T P and Ming D 2021a Enhancing transfer performance across datasets for brain-computer interfaces using a combination of alignment strategies and adaptive batch normalization *J. Neural Eng.* **18** 0460e5

Xu W, Liu X, Wang H and Zhou Y 2021b Observer-based adaptive neural network output-feedback control for nonlinear strict-feedback discrete-time systems *Int. J. Control Autom. Syst.* **19** 267–78

Xu X *et al* 2021c The transcranial direct current stimulation over prefrontal cortex combined with the cognitive training reduced the cue-induced craving in female individuals with methamphetamine use disorder: a randomized controlled trial *J. Psychiatr. Res.* **134** 102–10

Yan J, Wei Y, Wang Y, Xu G, Li Z and Li X 2015 Use of functional near-infrared spectroscopy to evaluate the effects of anodal transcranial direct current stimulation on brain connectivity in motor-related cortex *J. Biomed. Opt.* **20** 046007

Yang D *et al* 2019 Transcranial direct current stimulation for patients with pharmacoresistant epileptic spasms: a pilot study *Front. Neurol.* **10** 50

Yang D, Shin Y-I and Hong K-S 2021 Systemic review on transcranial electrical stimulation parameters and EEG/fNIRS features for brain diseases *Front. Neurosci.* **15** 629323

Yaqub M A, Hong K-S, Zafar A and Kim C-S 2021 Control of transcranial direct current stimulation duration by assessing functional connectivity of near-infrared spectroscopy signals *Int. J. Neural Syst.* **32** 2150050

Yaqub M A, Woo S-W and Hong K-S 2018 Effects of HD-tDCS on resting-state functional connectivity in the prefrontal cortex: an fNIRS study *Complexity* **2018** 1613402

Yaqub M A, Woo S-W and Hong K-S 2020 Compact, portable, high-density functional near-infrared spectroscopy system for brain imaging *IEEE Access* **8** 128224–38

Yoo H B, Ost J, Joos W, Van Havenbergh T, De Ridder D and Vanneste S 2018 Adding prefrontal transcranial direct current stimulation before occipital nerve stimulation in fibromyalgia *Clin. J. Pain* **34** 421–7

Zafar A and Hong K-S 2018 Neuronal activation detection using vector phase analysis with dual threshold circles: a functional near-infrared spectroscopy study *Int. J. Neural Syst.* **28** 1850031

Zafar A and Hong K-S 2020 Reduction of onset delay in functional near-infrared spectroscopy: prediction of HbO/HbR signals *Front. Neurorobot.* **14** 10

Zaghi S, Acar M, Hultgren B, Boggio P S and Fregni F 2010 Noninvasive brain stimulation with low-intensity electrical currents: putative mechanisms of action for direct and alternating current stimulation *Neuroscientist* **16** 285–307