Towards Home-based Therapy: The Development of a Low-cost IoT-based Transcranial Direct Current Stimulation System

Ahmad O. Alokaily, Ghala Almeteb, Raghad Althabiti, Suhail S. Alshahrani
Dept. of Biomedical Technology, College of Applied Medical Sciences
King Saud University, Riyadh, Saudi Arabia

***Abstract*—Transcranial direct current stimulation (tDCS), a neuromodulation technique that is painless and noninvasive, has shown promising results in assisting patients suffering from brain injuries and psychiatric conditions. Recently, there has been an increased interest in home-based therapeutic applications in various areas. This study proposes a low-cost, internet of things (IoT)-based tDCS prototype that provides the basic tDCS features with internet connectivity to enable remote monitoring of the system's usage and adherence. An IoT-enabled microcontroller was programmed with C++ to supply a specific dose of direct current between the anode and cathode electrodes for a predefined duration. Each tDCS session's information was successfully synchronized with an IoT cloud server to be remotely monitored. The accuracy of the resulting stimulation currents was close to the expected values with an acceptable error range. The proposed IoT-based tDCS system has the potential to be used as a telerehabilitation approach to enhance safety and adherence to home-based noninvasive brain stimulation techniques.**

Keywords*—IoT; Internet of medical things; tDCS; home-based; brain stimulation; cloud

I. Introduction

Neurostimulation has a long and rich history of gaining scholarly and public interest. The use of electricity in treating medical disorders was well documented in ancient times. The first documented evidence of electrical stimulation dates to ancient Greek, when Plato and Aristotle explained the torpedo fish's potential to generate therapeutic effects through its electric discharges [1, 2]. In the first century AD, Scribonius Largus reported that placing a live torpedo fish over a patient's scalp had curative effects in healing headaches and gout [2, 3]. Moreover, in the late 11th century, Ibn-Sidah suggested that torpedo fish could be used to treat epilepsy by placing them on the patients' foreheads [2, 4]. It is important to note that the electrical energy produced by electric fish is an alternating current. Nevertheless, in the 18th century, Giovanni Aldini was one of the first to use galvanism in medicinal applications, creating direct current stimulation [5, 6]. Since then, transcranial electrical stimulation has progressed from simple galvanic batteries to the most precise and advanced electronic microprocessors [1, 7].

From a biomedical engineering perspective, there are three electrical interactions between tissues and electronic systems. The first type is invasive, in which medical devices are surgically placed into the body to restore function. The second type is minimally invasive, when medical instruments are temporarily inserted for diagnosis and short-term treatment. The last type involves noninvasive devices used for monitoring, diagnosis, and treatment [8].

Transcranial direct current stimulation (tDCS) is a noninvasive brain stimulation technique that modulates cortical excitability by transmitting a low-intensity direct current to facilitate or inhibit cortical neuronal activities [9]. This approach has been shown to be safe and painless and to induce long-lasting excitability changes [10]. The cortical excitability changes caused by tDCS are presumed to follow the long-term potentiation (LTP) and long-term depression (LTD) neuroplasticity mechanisms [11]. Two standard stimulation montages are used in tDCS protocols. First, the anodal tDCS induces an enhancement in the cortical excitability (i.e., LTP-like effect) by depolarizing the resting membrane potential. Second, the cathodal tDCS induces a reduction in cortical excitability (i.e., LTD-like effect) by hyperpolarizing the resting membrane potential [12, 13].

In the past two decades, many studies have investigated the tDCS effects and their biomarkers in neuropsychiatric, cognitive, and motor disorders. tDCS is a promising and effective therapeutic tool in several conditions such as stroke, Parkinson's disease, Alzheimer's disease, depression, and schizophrenia [14]. For instance, a tDCS study was conducted on 10 clinically depressed patients. Half of them (five patients) received a 1mA anodal stimulation for 20 minutes per day, and the other half underwent sham treatment. The study showed that the tDCS stimulation led to a significant decrease in depression symptoms in the sample group compared with the sham group, suggesting tDCS can be an effective treatment for acute major depression [15]. In addition, tDCS antidepressant effects were shown to last up to 30 days after treatment [16].

It was also reported that almost 30% of patients with schizophrenia suffer from auditory hallucinations that are refractory to medications [14]. For this reason, the treatment of hallucinations in schizophrenia was studied using tDCS. Brunelin et al. [17] investigated the effect of tDCS on 30 patients with schizophrenia randomly assigned to receive an active 2mA tDCS or sham stimulation. A significant decrease in the severity of the hallucinations was observed, suggesting that tDCS could reduce symptoms of hallucinations, and the reduction lasted for up to three months [17]. Moreover, eight sessions of anodal tDCS treatment were applied to 13 patients diagnosed with Parkinson's disease and compared with a control group of 12 Parkinson's patients who received sham stimulation. Using 2mA for 20 minutes over three weeks led to an enhancement in the anodal tDCS stimulation group's upper extremity bradykinesia and gait [18]. Furthermore, tDCS showed promising results in enhancing cognitive performance in healthy populations [19]. For example, a study aimed to investigate the effect of tDCS on attention demonstrated a significant increase in concentration for a group who underwent 2mA tDCS when compared with those receiving 0.1mA [20].

Certain health-related events such as the global spread of COVID-19 have revealed the necessity of telehealth applications in various areas [21]. Such applications have proven to be a practical and effective approach by facilitating remote access and monitoring of healthcare services and reducing the associated contamination risks during the pandemic [21]. Furthermore, telehealth-based tDCS systems have therapeutic potential as they enable use for severely ill patients, enhance the recruitment rate in clinical studies, and optimize patients' and physicians' schedules [22].

Several investigators have developed a smart tDCS system to facilitate the in-home-based approach of tDCS. For instance, Sourav et al. [23] developed an Android application-controlled tDCS system with an adjustable headset to enhance the user's experience. This system was able to deliver a constant current of 0.1–2.5 mA and can store the session's information on external memory.

Additionally, Charvet et al. [24, 25] implemented supervision protocols of telemonitored tDCS and investigated the feasibility of monitoring and controlling the delivery of home-based tDCS sessions. The stimulation in these studies was applied using the Soterix mini-Clinical Trials tDCS device (Soterix Medical, New York, NY, USA). The tDCS sessions were monitored in real-time via the videoconferencing platform. It was concluded that telemonitored tDCS has a high compliance rate with no observed technical issues.

In this paper, a home-based tDCS device equipped with the internet of things (IoT) and controlled by a microcontroller is proposed. The internet cloud-based storage and monitoring system would be integrated with the traditional tDCS device to help healthcare providers monitor the system remotely. The main objective of the approach is to improve the patients' experience since it is a home-based device, self-administered with minimal training and cost-effective.

The remainder of this paper is organized as follows: Section II describes the main hardware components of the proposed IoT-based tDCS as well as the software structure and interface. Section III discusses the integration and validation of the proposed system. Finally, Section IV concludes the objective of this study and suggests future directions.

II. Methods

The proposed system consists of electrical hardware, custom-made software, and an IoT platform. The custom-made software controls the stimulation duration and intensity of the pulses, and the IoT platform registers session information on the cloud. The block diagram of the IoT-enabled home-based tDCS system is illustrated in Fig. 1.

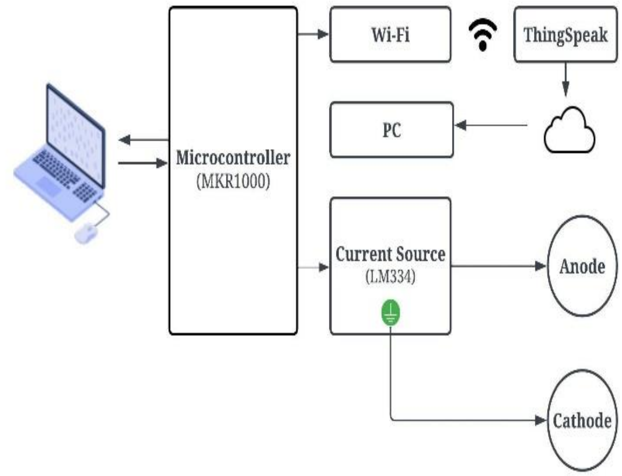

Fig. 1. Block Diagram of the Proposed IoT-based tDCS Device.

A. Hardware

The proposed IoT-based tDCS device consists of the following main hardware components:

- Computer: The proposed tDCS must be connected to a personal computer (PC) or notebook to power the system and send the commands to the microcontroller through a simple and user-friendly interface.
- Microcontroller: A low-cost consumer-grade microcontroller with internet connectivity (Arduino MKR1000) was used to control and regulate the operation of the proposed IoT-based tDCS system.
- Current regulators: Four three-terminal adjustable current sources (LM334-Z; Texas Instruments, USA) that operate with a sense voltage of 64 mV were connected in a parallel configuration to provide 0.5 mA in each loop, with a maximum current of 2 mA when the microcontroller triggered all loops. The LM334-Z was connected to digital pins 2, 3, 4, and 5.
- tDCS electrodes: A pair of commercially available tDCS electrodes (anode and cathode) as well as electrode wires, sponges, and an elastic headband for electrode placement (TheBrainDriver, USA) were used in the testing of the current tDCS system.
- Resistors: Four sets of resistors with an equivalent resistance of 128 Ω were connected in a parallel configuration to ensure that each loop in the tDCS circuitry provided 0.5 mA.
- Light-emitting diodes (LEDs): Four green LEDs were used as visual indicators of the current intensity.

B. Internet of Things (IoT) Platform

The ThingSpeak platform was used in the IoT-based tDCS device because it has the advantage of simplicity. A private channel was set to record, monitor, and retrieve real-time information on the stimulation duration and selected current intensity. The collected data are used for further analyses.

C. Software Architecture

The control and user interaction of the IoT-based tDCS prototype were programmed with an open-access Arduino IDE based on the C++ language. The flowchart of the system is shown in Fig. 2. A custom-made algorithm based on a switch statement to select an option from a set of defined discrete options was uploaded to the microcontroller (Arduino MKR 1000). The discrete options were constructed based on the most commonly used tDCS settings, which depend on the current intensity and stimulation duration. Thus, for this tDCS prototype, four current intensity options (low: 0.5 mA, medium: 1 mA, high: 1.5 mA, and very high: 2 mA) and three stimulation duration options (5, 10, and 20 minutes) were selected, defined, and coded to be received as a serial input entered by the user as illustrated in Table I. Based on the entered session's condition code, the microcontroller would activate all or some of the defined digital pins to supply the required current level for the selected time. Each digital pin (pins 2, 3, 4, and 5) on the microcontroller has a voltage of 3.3V when triggered, which is sufficient to supply 0.5 mA of direct current. Additionally, the operation of the IoT-based tDCS system could be terminated at any time during the session by pressing any keyboard character. Furthermore, data points were uploaded to the Thinkspeak cloud when the session was started and at the end of each session. The recorded data points report the selected stimulation current intensity and duration of each session.

D. System Testing and Validation

The amount of current produced by the system was continuously measured using a digital multimeter (DMM) for each condition separately and compared with the expected calculated values to ensure an accurate and stable operation of the proposed IoT-based tDCS device. The stimulation duration was also recorded and confirmed with each selected state. Moreover, the real-time data synchronization accuracy between the proposed device and the ThinkSpeak cloud was validated.

TABLE I. THE TDCS STIMULATION SESSION SETTINGS

Current Intensity levels	Session Setting Code (entered by users)	Delivered Current (mA)	Session Duration (min)
Low	L05	0.5	5
	L10		10
	L20		20
Medium	M05	1	5
	M10		10
	M20		20
High	H05	1.5	5
	H10		10
	H20		20
Very High	VH05	2	5
	VH10		10
	VH20		20

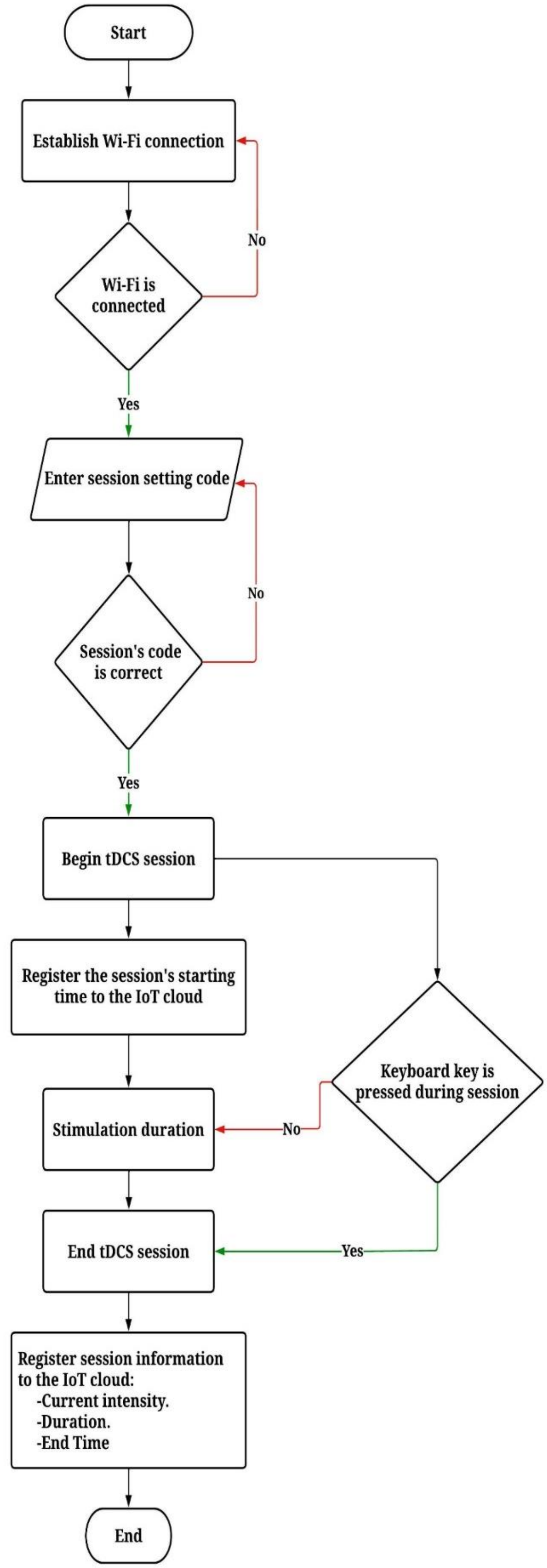

Fig. 2. Flowchart Illustrating the Operation Principle of the Proposed IoT-based tDCS Device.

III. Results and Discussion

A. System Integration

The IoT-based tDCS system hardware was securely placed in a compact, lightweight box (20 cm x 20cm x 9 cm), as shown in Fig. 3. The LEDs were lit up according to the selected amount of current passing between the anode and cathode.

B. System Validation

The IoT-based current outputs were measured using a DMM (GDM-451, GW Instek) for all current intensity settings and compared with the calculated current output. The measured currents were 0.58, 0.99, 1.6, and 2 mA for the low, medium, high, and very high settings, respectively. Furthermore, the error percentage of the output current intensity ranged from -1% to +16%, as shown in Table II. However, when the selected current was at the higher end of the system output (i.e., high and very high), the output current measured between the anode and cathode showed a minimum to 0% error compared with the expected current intensity. Compared with another study that implemented a mobile-controlled tDCS system [23], our approach has significantly lower error rates.

In addition, all the proposed tDCS current and duration settings were tested, and successful real-time information was uploaded to the private channel on the ThingSpeak platform, as shown in Fig. 4. Two recorded readings were registered on the ThingSpeak private channel as starting and ending points. The starting point was marked at 0, while the ending point was marked at the selected current intensity and duration. This provided the advantage of remote monitoring and registration of the tDCS session data, which can benefit healthcare providers.

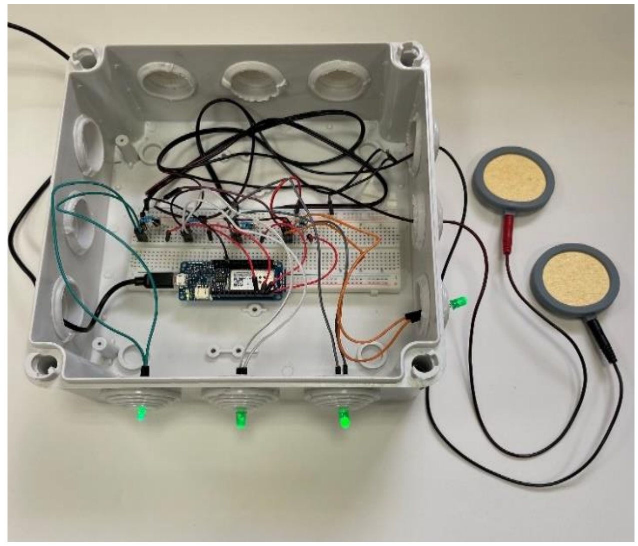

Fig. 3. Photograph of the IoT-based tDCS Device.

TABLE II. The Comparison between Calculated Current Intensity and Measured Current Intensity and the Error Percentage at Different Current Intensity Levels

Current Intensity Levels	Calculated Current Intensity (mA)	Measured Current Intensity (mA)	Error (%)
Low	0.50	0.58	+16.00%
Medium	1.00	0.99	-1.00%
High	1.50	1.60	+6.67%
Very High	2.00	2.00	0.00%

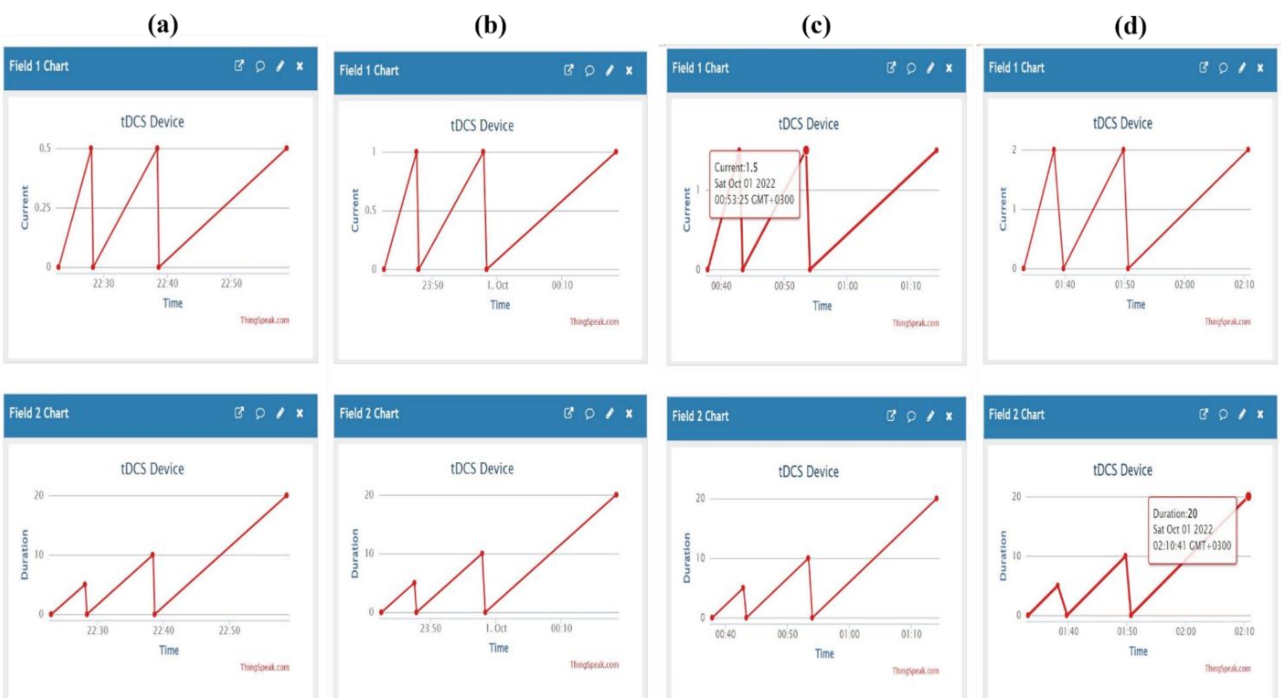

Fig. 4. The Figure Shows a Caption of the ThingSpeak Channel Information: Column (a) Exhibits Trials Taken at L05, L10, and L20 Settings. Column (b) Exhibits Trials Taken at M05, M10, and M20 Settings. Column (c) Exhibits Trials Taken at H05, H10, and H20 Settings. Column (d) Exhibits Trials Taken at VH05, VH10, and VH20 Settings.

Moreover, the proposed IoT-based tDCS system could be configured based on the subject's needs as prescribed by clinicians. Thus, the safety of delivering in-home tDCS sessions will be enhanced by ensuring that users can only apply the recommended current intensity and duration for each session.

IV. Conclusion

The present study focused on the feasibility of developing an IoT-based tDCS prototype using low-cost materials and a free-of-charge and accessible IoT platform. The use of IoT in our system could enhance the safety and adherence to home-based noninvasive research and therapy.

Future studies will be conducted to further improve the system's performance. Moreover, upon receiving the internal review board's approval, testing on human subjects will be investigated to evaluate the system's efficacy. Finally, the feasibility of a clinician remotely controlling the tDCS system over the internet will be explored.

References

[1] C. Sarmiento, D. San-Juan, and V. Prasath, "Brief history of transcranial direct current stimulation (tDCS): from electric fishes to microcontrollers," Psychological medicine, vol. 46, no. 15, pp. 3259-3261, 2016.

[2] A. Priori, "Brain polarization in humans: a reappraisal of an old tool for prolonged non-invasive modulation of brain excitability," Clinical neurophysiology, vol. 114, no. 4, pp. 589-595, 2003.

[3] G. Tsoucalas, M. Karamanou, M. Lymperi, V. Gennimata, and G. Androutsos, "The "torpedo" effect in medicine," International maritime health, vol. 65, no. 2, pp. 65-67, 2014.

[4] J. Delbourgo, A most amazing scene of wonders: electricity and enlightenment in early America. Harvard University Press, 2006.

[5] P. B. Fitzgerald, "Transcranial pulsed current stimulation: a new way forward?," vol. 125, ed, 2014, pp. 217-219.

[6] F. Z. d. S. Arêas, G. P. T. Arêas, and R. Moll Neto, "Giovanni Aldini and his contributions to non-invasive brain stimulation," Arquivos de Neuro-Psiquiatria, vol. 78, pp. 733-735, 2020.

[7] W. Paulus and A. Opitz, "Ohm's law and tDCS over the centuries," Clinical Neurophysiology: Official Journal of the International Federation of Clinical Neurophysiology, vol. 124, no. 3, pp. 429-430, 2012.

[8] F. X. Palermo and J. C. Castel, "Electrical stimulation device and method for the treatment of neurological disorders," ed: Google Patents, 2011.

[9] A. R. Brunoni et al., "Clinical research with transcranial direct current stimulation (tDCS): challenges and future directions," Brain stimulation, vol. 5, no. 3, pp. 175-195, 2012.

[10] M. A. Nitsche and W. Paulus, "Sustained excitability elevations induced by transcranial DC motor cortex stimulation in humans," Neurology, vol. 57, no. 10, pp. 1899-1901, 2001.

[11] C. J. Stagg, A. Antal, and M. A. Nitsche, "Physiology of transcranial direct current stimulation," The journal of ECT, vol. 34, no. 3, pp. 144-152, 2018.

[12] T. Tanaka, Y. Isomura, K. Kobayashi, T. Hanakawa, S. Tanaka, and M. Honda, "Electrophysiological effects of transcranial direct current stimulation on neural activity in the rat motor cortex," Frontiers in Neuroscience, vol. 14, p. 495, 2020.

[13] J. Green, S. Jang, J. Choi, S. C. Jun, and C. S. Nam, "Transcranial Direct Current Stimulation (tDCS): A Beginner's Guide for Neuroergonomists," in Neuroergonomics: Springer, 2020, pp. 77-101.

[14] S. M. Szymkowicz, M. E. McLaren, U. Suryadevara, and A. J. Woods, "Transcranial direct current stimulation use in the treatment of neuropsychiatric disorders: a brief review," Psychiatric annals, vol. 46, no. 11, pp. 642-646, 2016.

[15] F. Fregni, P. S. Boggio, M. A. Nitsche, M. A. Marcolin, S. P. Rigonatti, and A. Pascual-Leone, "Treatment of major depression with transcranial direct current stimulation," 2006.

[16] P. S. Boggio et al., "A randomized, double-blind clinical trial on the efficacy of cortical direct current stimulation for the treatment of major depression," International Journal of Neuropsychopharmacology, vol. 11, no. 2, pp. 249-254, 2008.

[17] J. Brunelin et al., "Examining transcranial direct-current stimulation (tDCS) as a treatment for hallucinations in schizophrenia," American Journal of Psychiatry, vol. 169, no. 7, pp. 719-724, 2012.

[18] D. H. Benninger et al., "Transcranial direct current stimulation for the treatment of Parkinson's disease," Journal of Neurology, Neurosurgery & Psychiatry, vol. 81, no. 10, pp. 1105-1111, 2010.

[19] A. Pisoni, G. Mattavelli, C. Papagno, M. Rosanova, A. G. Casali, and L. J. Romero Lauro, "Cognitive enhancement induced by anodal tDCS drives circuit-specific cortical plasticity," Cerebral Cortex, vol. 28, no. 4, pp. 1132-1140, 2018.

[20] B. A. Coffman, M. C. Trumbo, and V. P. Clark, "Enhancement of object detection with transcranial direct current stimulation is associated with increased attention," BMC neuroscience, vol. 13, no. 1, pp. 1-8, 2012.

[21] A. C. Smith et al., "Telehealth for global emergencies: Implications for coronavirus disease 2019 (COVID-19)," Journal of telemedicine and telecare, vol. 26, no. 5, pp. 309-313, 2020.

[22] A. Cucca, K. Sharma, S. Agarwal, A. S. Feigin, and M. C. Biagioni, "Tele-monitored tDCS rehabilitation: feasibility, challenges and future perspectives in Parkinson's disease," Journal of neuroengineering and rehabilitation, vol. 16, no. 1, pp. 1-10, 2019.

[23] M. S. U. Sourav, A. Rahman, A. Al Mamun, and F. M. Alamgir, "Standard Transcranial Direct Current Stimulation (tDCS) Model," International Journal of Computer Networks and Communications Security, vol. 5, no. 12, pp. 264-270, 2017.

[24] L. E. Charvet, B. Dobbs, M. T. Shaw, M. Bikson, A. Datta, and L. B. Krupp, "Remotely supervised transcranial direct current stimulation for the treatment of fatigue in multiple sclerosis: results from a randomized, sham-controlled trial," Multiple Sclerosis Journal, vol. 24, no. 13, pp. 1760-1769, 2018.

[25] L. Charvet et al., "Remotely supervised transcranial direct current stimulation increases the benefit of at-home cognitive training in multiple sclerosis," Neuromodulation: Technology at the Neural Interface, vol. 21, no. 4, pp. 383-389, 2018.