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Aim and Scope

NeuroRegulation is a peer-reviewed journal providing an integrated, multidisciplinary perspective on clinically relevant research, treatment, and public policy for neurofeedback, neuroregulation, and neurotherapy. The journal reviews important findings in clinical neurotherapy, biofeedback, and electroencephalography for use in assessing baselines and outcomes of various procedures. The journal draws from expertise inside and outside of the International Society for Neurofeedback and Research to deliver material which integrates the diverse aspects of the field. Instructions for submissions and Author Guidelines can be found on the journal website (http://www.neuroregulation.org).

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RESEARCH PAPERS

NeuroRegulation

Using Neurofeedback to Lower PTSD Symptoms

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Abstract

This study examines the effectiveness of neurofeedback training for individuals presenting with a primary concern of posttraumatic stress disorder symptoms. The present study includes 21 adult clients with 62% (*n* = 13) self-reporting as female. Participants completed pre- and postassessments including the Davidson Trauma Scale and Inventory of Altered Self-Capacities and participated in neurofeedback training sessions twice a week for one academic semester. Neurofeedback training involved decreasing 2–6 Hz and 22–36 Hz while increasing 10–13 Hz with a placement of T4 as the active site and P4 as the reference site. Study findings demonstrated statistically significant improvement in affect regulation and trauma symptom severity and frequency. We present limitations and implications for future research.

Keywords: PTSD; neurofeedback; trauma; affect regulation

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Introduction

According to the National Center for posttraumatic stress disorder (PTSD), around 8% of the population will experience PTSD symptoms at some point in their lives. PTSD used to be associated mainly with veterans and refugees, but we now know that PTSD can occur after any witnessed or experienced upsetting traumatic event. The experience of a traumatic event can also lead to maladaptive outcomes in social behaviors, physiology, emotions, and cognitions including affect dysregulation. PTSD can develop in nearly one in eight adult trauma survivors (Jones, Rybak, & Russell-Chapin, 2017). Exposure to a traumatic event may lead to maladaptive stress responses. These responses serve as signifiers of how the body remembers and re-experiences stressors when triggered (Othmer & Othmer, 2009). These stress responses include but are not limited to over arousal, hypervigilance, flash backs, nightmares, and fear. Survivors of trauma may also have difficulty with affective prosody and lack the ability to properly interpret emotional cues of language (Jones et al., 2017).

There are various therapeutic approaches to treating PTSD and other related trauma symptoms. Previous forms of treatment include prolonged exposure therapy which is an integration of imaginal exposure and in vivo exposure (McLean & Foa, 2013). The clinician exposes the client and grounds them in real time to teach coping skills. This is a form of cognitive behavior therapy (CBT) and similar to cognitive processing therapy (CPT), another popular treatment for PTSD. CPT aims to reframe maladaptive thinking and build new skills to identify and address these maladaptive thoughts (Schumm, Dickstein, Walter, Owens, & Chard, 2015). An additional form of treatment that addresses maladaptive thoughts is eye movement desensitization and reprocessing (EMDR). EMDR desensitizes traumatic memories by having the client retell the event while watching the clinician's rapid finger movements (National Library of Medicine, 2002). The common theme amongst PTSD treatment is an attention to the thoughts and memories associated with the event. Although there are various approaches that target these thoughts and memories once told aloud to the clinician, the goal of neurofeedback is to create better function in the affected areas of the brain through brainwave training (Othmer & Othmer, 2009).

Neurofeedback, formerly known as electroencephalography (EEG) biofeedback, is a form of biofeedback that uses real-time displays of neural activity to teach the client self-regulation of brain function. Neurofeedback protocols supply participants with audio or visual feedback, or both, which trains them to maintain certain frequency bands (Marzbani, Marateb, & Mansourian, 2016). From this viewpoint, mental health concerns present as variations in brain wave frequencies. This modality improves health, performance, and the physiological changes which often occur in conjunction with changes to thoughts, emotions, and behavior. Neurofeedback uses precise protocols for the purposes of optimizing brain wave activity, done subconsciously through a loop process, using operant conditioning (Sitaram et al., 2016). Reports of neurofeedback as an effective treatment for PTSD date back to the original study by Peniston and Kulkosky (1991) on alpha–theta neurofeedback for Vietnam veterans. A pilot study on neurofeedback for chronic PTSD by Gapen et al. (2016) showed promising results, with a follow-up randomized, waitlist-controlled study demonstrating statistically robust results (van der Kolk et al., 2016).

Using a waitlist control, van der Kolk et al. (2016) examined the effect of neurofeedback treatment for those who met the criteria for chronic PTSD. Participants in the experimental group received neurofeedback training twice a week for up to 30 minutes for a total of 24 sessions. Training focused on decreasing 2–6 Hz and 22–36 Hz while increasing 10–13 Hz with a placement of T4 as the active site and P4 as the reference site. The authors found those who received neurofeedback training had significant improvements such as improvement of PTSD symptomatology, affect regulation, tension reduction activities, identity impairment, and abandonment concerns (van der Kolk et al., 2016). van der Kolk's (2016) underlying theme of "rewiring" the brain as a necessary proponent of change supports the argument that traditional therapeutic methods do not suffice in treating PTSD. Interventions such as neurofeedback can change the way in which we treat mental health disorders as well as how we conceptualize them. The intent of this study is to provide further evidence that neurofeedback provides significant care through neuronal regulation and stabilization.

Purpose of Study

This study examined the effectiveness of neurofeedback training for individuals presenting with a primary concern of PTSD symptoms. The overarching goal was to evaluate the effectiveness of neurofeedback training on lowering PTSD symptoms using the same protocol and symptom scales as van der Kolk et al. (2016). Therefore, we examined the following research questions:

1. Is there a statistically significant difference on participant self-reported PTSD symptom severity and frequency as measured by the Davidson Trauma Scale following neurofeedback training?
2. Is there a statistically significant difference on participant self-reported emotion regulations and interpersonal processes as measured by the Inventory of Altered Self-Capacities following neurofeedback training?

We anticipated improvement in PTSD symptom severity and frequency and affect regulation. We based our hypotheses on the literature and statistically significant findings of van der Kolk et al. (2016).

Method

This within-subjects research design occurred in a counseling center in a university counseling department with the primary purpose of training graduate-level counseling students. The present study evaluated the effectiveness of neurofeedback to increase affect regulation and reduce PTSD related symptoms in adults.

Participants

The present study included data from a total of 21 clients ranging in age from 18 to 68 (*M* = 40.86, *SD* = 14.32) with 38% (*n* = 8) of clients self-reporting as male and 62% (*n* = 13) self-reporting as female (see Table 1). Clients from the surrounding community seeking neurofeedback services for PTSD and trauma-related symptoms contacted the counseling department clinic at a southern United States university. This counseling center was well situated geographically and demographically and was one of the few clinics in its community providing free mental health services to the general public. The counseling department clinic has a history of providing services free of charge to the surrounding community. Thus, the primary method of recruitment included referrals from practitioners in the community. Inclusion criteria consisted of primary trauma symptoms, availability, and age requirements. Clients agreed to attend a minimum total number of 15 neurofeedback training sessions, twice per week. Clients received neurofeedback services free of charge.

Table 1
Client Demographics

Client #	Age	Gender	Number of Sessions
1	30	F	15
2	37	M	11
3	18	F	18
4	46	M	18
5	45	F	16
6	18	F	13
7	54	M	9
8	43	F	21
9	33	F	16
10	48	F	15
11	41	M	11
12	47	F	17
13	49	F	17
14	67	F	13
15	68	M	13
16	40	M	19
17	27	F	14
18	18	M	18
19	56	F	19
20	30	F	15
21	30	M	17
M(*SD*)	40.86(14.32)	--	15.48(3.04)

Clinicians

Student and volunteer clinicians provided neurofeedback services. Student clinicians consisted of clinical mental health master-level students, school counseling master-level students, and counselor education and supervision doctoral-level students within counseling programs nationally accredited by the Council for Accreditation of Counseling and Related Education Programs (CACREP). Volunteer clinicians consisted of faculty and/or credentialed local clinicians such as licensed professional counselors, psychologists, neuropsychologists, nurse practitioners, and social workers. All clinicians (i.e., volunteer, student) previously completed the Biofeedback Certification International Alliance (BCIA) requirements for didactic coursework for neurofeedback and are under the supervision of a certified and licensed supervisor. Regarding the completed didactic coursework, all student clinicians completed an introduction to neurofeedback course offered in their program of study that is based on the certification requirements of BCIA. At the time of data collection, student clinicians enrolled in advanced neurofeedback or practicum of neurofeedback courses provided the neurofeedback services to the study participants.

Measures

Davidson Trauma Scale. The Davidson Trauma Scale (DTS; Davidson, 1996) is a 17-item self-report measure that assesses PTSD symptoms as defined in the *Diagnostic and Statistical Manual of Mental Disorders* (*DSM-IV;* Davidson, 1996). The DTS has three symptoms clusters: Intrusion, Avoidance/ Numbing, and Hyperarousal with scores ranging from 0 to 136 (Davidson, 1996). Measures of Severity and Frequency of symptoms occur on a 5-point scale (0 = *Not at all* to 4 = *Every day*). Example items include “Have you been upset by something that reminded you of the event?” and “Have you felt distant or cut off from other people?” (Davidson, 1996). The DTS shows good reliability with a high Cronbach’s alpha of over .90 for the entire scale as well as the Frequency and Severity scales (Davidson, 1996). The DTS demonstrated a preintervention Cronbach’s alpha of .79 with two removed cases due to missing item level data and a postintervention Cronbach’s alpha of .95 for the current sample.

Inventory of Altered Self-Capacities. The Inventory of Altered Self-Capacities (IASC; Briere, 2000) is a 63-item self-report. The IASC consists of seven scales that assess self-related psychological difficulties using the following domains: Interpersonal Conflicts, Idealization-Disillusionment, Abandonment Concerns, Identity Impairment, Susceptibility to Influence, Affect Dysregulation, and Tension Reduction Activities. Of those scales, Identity Impairment and Affect Dysregulation each have two subscales. Self-awareness and Identity Diffusion comprise the Identity Impairment scale and Affect Instability and Affect Skills Deficits are the two subscales within the Affect Dysregulation scale.

Ratings of items occur according to frequency of occurrence over the last six months on a 5-point Likert-type scale (1 = *Never* to 5 = *Very often*). Example items include “Doing things to stop feeling so much pressure or pain inside,” “Suddenly hating someone you used to like a lot,” and “Wishing you could calm down but not being able to” (Briere & Runtz, 2002). The IASC shows good reliability with the Cronbach’s alpha ranging from .78 to .93 across its scales and subscales (Briere & Runtz, 2002). In this sample, the IASC demonstrated a preintervention Cronbach’s alpha of .97 and a postintervention Cronbach’s alpha of .96 with two removed cases due to missing item-level data.

Data Collection Procedures. The Institutional Review Board at a southern United States university approved this study. During the preintervention phase, clients completed the informed consent process and both outcome-based measures (i.e., DTS, IASC). Clients also completed both outcome-based measures postintervention. This section describes procedures for the neurofeedback training process.

Clinicians utilized BrainMaster Atlantis two-channel amplifiers (BrainMaster Technologies, Inc., Bedford, OH) and BioExplorer software (CyberEvolution, Inc., Seattle, WA) for neurofeedback training. Clinicians cleaned the neurofeedback sites with rubbing alcohol and PCI prep pads. Next, clinicians applied Ten20 EEG conductive paste to gold-plated electrodes and placed them on a client’s scalp. Throughout the neurofeedback training process, clinicians noted the impedance levels and adjusted as needed to ensure a reading of less than five kΩ (Jones, 2015).

The range of attended sessions was 9–21 (*M* = 15.48, *SD* = 3.04) for approximately 20 minutes per session, twice per week, over the course of one academic semester. The neurofeedback clinicians asked clients to halt the consumption of caffeine or other potential nonessential substances on neurofeedback training days. During the training sessions, protocols consisted of amplitude uptraining and/or downtraining preselected frequency bands consistent with van der Kolk et al. (2016). The thresholds are set at the beginning of each session with an ideal reward rate of 50%. Following the procedures of van der Kolk et al. (2016), training sites for all clients include T4 as the active site, P4 as the reference site, and A1 as the ground. Further, the aim for neurofeedback training is for clients to decrease brain activity of 2–6 Hz and 22–36 Hz and increase 10–13 Hz (van der Kolk et al., 2016). Due to the varying degree of counseling skills present among the student clinicians and volunteers, clinicians received instructions to limit counseling interventions to those necessary for neurofeedback training, such as shaping behavior, positive reinforcement, and emotional support.

Statistical Analysis. We used the Statistical Package for the Social Sciences (SPSS) software version 25 (SPSS, 2017) for all statistical analyses. Before analysis, we examined cases for missing data, outliers, and normality. The percentage of participants missing data ranged from 0% for the DTS to .90% for the IASC. Following Cohen’s (1988) conventions, a medium effect size of .5, error probability of .05, and 21 participants, A post-hoc G*Power analysis determined that the current sample size of this study would yield a power of .59.

Results

We used a paired samples *t*-test to measure pre–post comparisons of the DTS symptom clusters, Severity, Frequency, and Total scores which resulted in statistically significant improvements. Table 2 presents a summary of these results. On the Total DTS score, for all subjects, the mean of the prescores was 78.10 (*SD* = 25.02) and the mean of the postscores was 61.52 (*SD* = 35.38). The paired samples *t*-test yielded a statistically significant improvement, with *t*(20) = 2.95, *p* = .008, with a medium effect size (*d* = .64). See Table 3 for the pre–post DTS scores for each client.

On the IASC, six of the seven scales demonstrated statistically significant improvement. In addition, we found significant mean differences for Identity Diffusion, one of two Identity Impairment subscales, and both of the Affect Dysregulation subscales (i.e., Affect Skills Deficits, Affect Instability). We present a summary of these results in Table 4.

Discussion

This study builds on the findings of van der Kolk et al. (2016) by examining the effectiveness of neurofeedback training for individuals presenting to a counseling center in a university counseling department with a primary concern of PTSD symptoms. The overarching goal was to evaluate the effectiveness of neurofeedback training to lower PTSD symptoms using an existing protocol previously evaluated in a randomized, waitlist-controlled efficacy trial. van der Kolk et al. (2016) found 24 sessions of neurofeedback resulted in significant improvements in PTSD symptomology and

Table 2
Davidson Trauma Scale

	Pre *M*(*SD*)	Post *M*(*SD*)	*t(df)*	*p*	*d*
Intrusion	21.38(9.98)	17.57(11.14)	1.94(20)	.067	.42
Avoidance/Numbing	30.81(11.02)	24.57(14.82)	2.20(20)	.040	.48
Hyperarousal	25.90(9.14)	19.48(11.83)	3.44(20)	.003	.75
Severity	38.67(14.98)	30.90(17.99)	2.41(20)	.025	.53
Frequency	39.43(11.57)	30.71(18.20)	3.39(20)	.003	.74
Total	78.10(25.02)	61.52(35.38)	2.95(20)	.008	.64

Table 3
Davidson Trauma Scale Total Scores

Client #	Pre	Post
1	87	72
2	113	114
3	41	14
4	96	127
5	50	31
6	79	86
7	58	22
8	63	72
9	103	73
10	58	19
11	96	69
12	93	108
13	121	105
14	92	61
15	105	40
16	88	66
17	75	92
18	34	55
19	38	11
20	68	22
21	82	33
M(*SD*)	78.10(25.02)	61.52(35.38)

Note. $t(20) = 2.95$, $p = .008$

areas of psychological functioning capacity (i.e., affect regulation, tension reduction activities, identity impairment, abandonment concerns) using T4 as the active site and P4 as the reference site. The average session attendance total for the present study was 15 sessions. This study produced similar, promising results. Findings revealed statistically significant improvement in avoidance/numbing, hyperarousal, severity, frequency, and overall total score for the DTS. For instance, the Cohen's effect size value for the DTS overall total score ($d = .64$) suggested a moderate practical significance, whereas van der Kolk and colleagues (2016) found a large effect size ($d = .92$) difference between pre- and postassessment.

Similar to van der Kolk et al.'s (2016) findings, neurofeedback participants in the present study demonstrated statistically significant improvements in affect regulation as the aim of neurofeedback is neuronal regulation and stabilization. More specifically, the present study resulted in statistically significant improvements in measures of interpersonal conflicts, idealization-disillusionment, abandonment concerns, identity impairment, susceptibility to influence, affect dysregulation, and tension reduction for the IASC. As shown in Table 4, effect sizes for these measures demonstrated a range of small to large practical significance.

In addition, van der Kolk et al. (2016) expressed how neurofeedback can be a promising change agent for habitual dysfunctional neuronal patterns and highlighted its potential of becoming widely available in community settings as it is economically accessible and it does not have to be administered out of a research clinic such as the present study. Although

Table 4
Inventory of Altered Self-Capacities

	Pre *M*(*SD*)	Post *M*(*SD*)	*t(df)*	*p*	*d*
Interpersonal Conflicts	23.42(7.81)	20.47(8.17)	2.40(18)	.027	.55
Idealization-Disillusionment	19.21(6.07)	16.00(3.46)	2.54(18)	.021	.58
Abandonment Concerns	23.05(9.17)	18.58(8.78)	3.41(18)	.003	.78
Identity Impairment	26.63(9.15)	22.37(8.65)	2.28(18)	.035	.52
Self-Awareness	16.32(5.58)	14.47(5.98)	1.40(18)	.178	.32
Identity Diffusion	9.89(4.69)	7.89(3.64)	2.41(18)	.027	.55
Susceptibility to Influence	19.32(7.92)	15.00(5.56)	3.12(18)	.006	.72
Affect Dysregulation	26.79(8.22)	22.79(8.78)	2.91(18)	.009	.67
Affect Skill Deficits	14.32(5.53)	12.32(5.19)	2.39(18)	.028	.55
Affect Instability	12.47(3.42)	9.95(3.49)	3.66(18)	.002	.84
Tension Reduction	18.42(5.94)	15.79(5.46)	1.99(18)	.062	.46

neurofeedback is more affordable than other neuroimaging methods, the cost of training, equipment, software, and supplies (e.g., electrodes, conductive paste) is a significant barrier for settings with limited resources and funding (Beeson & Field, 2017).

Furthermore, for the present study, both student and volunteer clinicians provided neurofeedback services. Student clinicians included those enrolled in an accredited counseling graduate degree program and volunteer clinicians included both community members and faculty from the study's institution. While student and volunteer clinicians completed their didactic coursework, they were still engaging in components of their mentoring and practical skills training and had not yet completed their neurofeedback certification exam. There were benefits to incorporating volunteer clinicians, some of which are local mental health professionals in the community. This had a positive impact of creating networks with student clinicians, as well as providing "real world" perspectives of the local mental health community. However, while this created a greater level of feasibility and accessibility to community engagement and pursuing neurofeedback research, there were also limitations to having variance in training and skill level, which the authors discuss further in the limitations section.

Limitations and Implications for Future Research

There are important limitations in the present research to consider prior to the interpretation of findings. Concerning the demographics of the participants, researchers only collected gender and age preventing the researchers from analyzing the data beyond the current scope and geographically. The study also lacked a control or sham group and had a fairly small sample size which limits the power but also risks Type II errors and generating biased interpretations. Furthering this, the psychometrics of the scales should need further examination as they are at least two decades old and may not be relevant to the participants in this research, ultimately impacting the reliability, validity, and fairness. Methodological limitations include the within-subjects design with no control group. Also, in relation to the number of sessions attended by each individual, client participation in neurofeedback training varied. Not all clients attended the agreed upon 15 sessions. As such, the researchers set a session cut-off of nine sessions for inclusion in the present study. Removal of other client data not meeting this criterion accounts for the limited sample size and resulting statistical interpretation. Thus, replication of this study may have alternative results considering the sample size, demographics, and psychometric relevance.

There are many implications of this study in relation to future research directions and approaches to neurofeedback in the mental health field. This present research and van der Kolk et al.'s (2016) study focused on T4 and P4 locations, however multicultural and individual differences could impact how this data could be interpreted. While there are emerging neuro-informed frameworks regarding mental health disorders, suggesting abnormalities in neural connectivity and brain wave patterns (van der Kolk et al., 2016), the present researchers strongly suggest contextualizing individuals by understanding their sociocultural and social justice implications. Therefore, the present researchers encourage promoting individual protocols and within-subject designs but not comparisons between participants and across populations and genders.

There is a colonizing to mental health and a lack of cultural diversity in the literature that researchers should acknowledge as these factors impact neurofeedback data and results could deviate from the image of a "normal" brain and regular levels of stress. Given that there are biological mechanisms of a life of marginality (Douthit & Russotti, 2017), researchers have an ethical responsibility to acknowledge the social justice implications of their research. In regard to future studies, a neuroecological approach (Sherry, 2006; van Dijk & Myin, 2019) could create a more ethical and social justice-oriented paradigm to investigate similar research.

Researchers should also consider epigenetics and psychoneuroimmunology, or PNI, in how this relates to all of neuroscience, neurofeedback research, and understanding the mind–brain connection. In specific regards to research relating to anxiety, stress, and PTSD, epigenetic modifications of the hypothalamic pituitary adrenal (HPA) axis gene can create more reactivity to stress and a predispositional vulnerability to psychological manifestations of chronic stress (Douthit & Russotti, 2017). Whereas PNI has the role of translating chronic environmental stress into physiological susceptibility in individuals, these factors can impact the immune system and encourage inflammation, creating a stress-immune dysregulation relationship that relates to mind–body communication which affects overall mental health and predisposed risks or vulnerabilities to future stress (Douthit & Russotti, 2017).

Future research should consider how to advise counselors and counselor educators who intend to use neurofeedback in education and practice as well as conceptualize how to standardize training and access to equipment. This study did not investigate the combination of talk therapy or counseling with neurofeedback; future research should further investigate the partnering of both. Finally, future researchers should also consider using qualitative methods to gain an understanding of participant experiences with neurofeedback training used for the treatment of PTSD and trauma-related symptoms.

Conclusion

This study explored specific neurofeedback protocols for trauma treatment. The results supported our hypotheses that neurofeedback would significantly improve PTSD symptom severity and frequency and affect regulation. Although this study contains limitations, the results are promising for using neurofeedback to treat trauma. Neurofeedback can better inform interventions and provide a physical representation of mental manifestations as well their relationship to emotions, physiology, and social justice (Douthit & Russotti, 2017). Future mental health models should account for emerging mind–body paradigms but also understand the social justice implications associated with them. Future research is essential and can begin with the implications for research presented in this article.

Author Declarations

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NeuroRegulation

Effect of Threshold Setting on Neurofeedback Training

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Abstract

This study aimed to confirm the effect of threshold setting on the performance of neurofeedback training. The experimental conditions used to confirm the effect of the different threshold settings on the degree of electroencephalographic (EEG) changes in the initial training conditions were unfamiliar to neurofeedback. Rewards were presented in *low*, *medium*, and *high* frequency groups according to the different threshold settings. The sensory-motor rhythm (SMR; 12–15 Hz) neurofeedback protocol was performed for all groups. We looked at whether the posttraining brain wave increases were significant in each group compared to the brain waves during training. The SMR protocol was performed in a single session and consisted of four blocks totaling 10 minutes. EEG data was collected before training as a baseline, during training, and posttraining. The results of the group analysis showed that the mean SMR value of the posterior EEG in the high frequency group was significantly higher than the SMR value in the first EEG block. The threshold settings affected learning in neurofeedback training. It was found that initially setting the threshold value for easy compensation was more effective than the setting for hard compensation.

Keywords: neurofeedback; rewards; threshold; learning theory; brain wave

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Introduction

Neurofeedback is used in a wide range of areas—such as muscle activity, skin temperature, respiration, heart rate, and blood pressure—and is also known as electroencephalographic (EEG)-biofeedback (Egner & Gruzelier, 2003; Schwartz & Andrasik, 2017).

Neurofeedback trains the brain's electrophysiological processes (Demos, 2005; Gupta, Afsar, Yadav, Shukla, & Rajeswaran, 2020; LaVaque, 2003). Neurofeedback is widely used for the treatment of attention-deficit/hyperactivity disorder (ADHD), autism spectrum disorders, cognitive learning disorders, epilepsy, alcohol abuse, substance abuse, posttraumatic stress disorder, depression, sleep, and pain, as well as various nonclinical objectives, such as performance improvement and the cognitive enhancement of attention and memory (Niv, 2013; Roy, de la Vega, Jensen, & Miró, 2020; Weber, Ethofer, & Ehlis, 2020). The majority of those with neurological and medical disabilities are known to exhibit abnormal EEG patterns compared to the general population (Hammond, 2007; LaVaque, 2003; Yucha & Montgomery, 2008). Therefore, in neurofeedback, it is important to understand these abnormal electrophysiological characteristics so that effective training can be established for such patients (Hammond, 2007; LaVaque, 2003; Yucha & Montgomery, 2008).

Existing methods to regulate brain activity other than neurofeedback include surgery, drugs, and electrical therapy (Demos, 2005; LaVaque, 2003). However, these methods are invasive and pose a risk of adverse side effects (Dunn et al., 2011; Niv, 2013). Recent studies have focused on finding noninvasive and safe neuromodulation techniques that help control brain activity. Neurofeedback is the most widely used technique among these (Coben & Evans, 2010). Neurofeedback has a wide range of applications, such as cognitive training to improve concentration and memory, reducing tension in athletes, and improving medical skills (Doppelmayr &

Weber, 2011; Pacheco, 2011; Ros et al., 2009). Besides, it has been found to be beneficial in stimulating the body's natural healing potential and helping clients to become more active in their care (Hill & Castro, 2009; Niv, 2013; Redwood, 2000).

Neurofeedback is based on neurobiological findings, but the implementation and reward methods follow the principles of psychotherapy (Morales-Quezada et al., 2019; Strehl, 2014). Discussion regarding the types of rewards and the amount and frequency of feedback is still ongoing (Sherlin et al., 2011; Sulzer et al., 2013). According to learning psychology, reward-given behavior is more likely to reappear. Neurofeedback provides visual and auditory rewards when the targeted power of the EEG is increased, decreased, or maintained (Strehl, 2014). The trainee identifies real-time reflections of his or her mental state and provides feedback accordingly. This feedback helps the trainees adjust their body and mind accordingly (Gilbert & Moss, 2003; Yuan & Bieber, 2003; Yucha & Montgomery, 2008).

Feedback in neurofeedback training (NFT) is comparable to rewards in learning psychology and depends on the target of the EEG (Collura, 1999; Collura, 2007; Hammond, 2007). Just as learning psychology provides rewards (e.g., praise, food, or token) to maintain target behavior, NFT provides feedback signals (e.g., visual or auditory stimulation) to increase or decrease the targeted brain waves (Dayan & Balleine, 2002; Sherlin et al., 2011; Watanabe, Sasaki, Shibata, & Kawato; 2017).

The type of feedback (reinforcements) in NFT is related to the purpose and characteristics of the training. In protocols such as theta and alpha increase and high beta reduction for relaxation and the reduction of anxiety and arousal, subtle musical sounds, nonpatterned sounds, and natural sounds were used as rewards (Batty, Bonnington, Tang, Hawken, & Gruzelier, 2006). Protocols such as raising SMR are related to cognitive awakening in physical relaxation situations. Some examples of techniques that help the trainee concentrate are a car moving in a racing game, a bell sound when a goal is reached, or a change in the color of the graph provided (Cortoos, De Valck, Arns, Breteler & Cluydts, 2010; Doppelmayr & Weber, 2011).

The neurofeedback training follows the principle of learning psychology, emphasizing the importance of setting an appropriate frequency of reinforcement (Skinner, 1953). If a reward is not received due to the difficulty of the action, learning does not progress, and motivation is lowered. As a result, there will not be much improvement seen even after completing the sessions. Contrastingly, if the tasks are too easy, subjects can lose interest and stop trying, making the training less effective. In summary, this means that if proper compensation is not provided during learning behavior, learning does not occur (Terborg & Miller, 1978). Although neurofeedback studies have been closely related to learning theory and compensation plans, it has been challenging to find studies that deal with reinforcement schedules or the ease of obtaining rewards, which affects the effectiveness of training (Grice, 1948; Hardt & Kamiya, 1976; Ossadtchi, Shamaeva, Okorokova, Moiseeva, & Lebedev, 2017).

The standard for determining the difficulty of training when performing neurofeedback is called the threshold, and the frequency of compensation to be assigned to the trainee can vary depending on the threshold (Bauer, Fels, Royter, Raco, & Gharabaghi, 2016; Collura, 2007). Existing neurofeedback studies provide feedback by setting thresholds in various ways (Vernon et al., 2009). First, the absolute value is added to or subtracted from the mean value of the EEG, and the threshold value is set 1–2 points higher or 0.2–0.6 points lower than the mean value when aiming for a decrease or increase, respectively (Lubar, Swartwood, Swartwood, & O'Donnell, 1995; Thompson & Thompson, 1998). Second, the threshold can be calculated by multiplying the average power by a specific value. The mean value of the frequency band to be increased from baseline is multiplied by 0.8, and the mean value of the frequency band to be suppressed is multiplied by 1.2 to 1.6 (Egner, Zech & Gruzelier, 2004; Gruzelier, 2014a; Ros et al., 2009). Both of these methods can help to set the difficulty level and compensation by setting the threshold value. Third, the threshold value can be set to maintain a range of success rates (%; compensated time / total time x 100) during the session (Arns, Feddema, & Kenemans, 2014; Sime, 2004). For example, when training the band to be increased, either a 25% enhancement rate or a 65% success rate should be maintained. The higher the enhancement rate, the easier it is to get compensation and vice versa. Third, set a certain reinforcement rate so that it can be compensated for a percentage (%) regardless of the performance level. However, this has limitations as the subjects are rewarded the same even when they are not performing better (Arns et al., 2014; Ros et al., 2009). However, the second method can compensate for the limitations of the third in that the subject is compensated only when the trainee is performing well (Egner et al., 2004; Ros et al., 2009). Recently, the second and third methods have been used in neurofeedback studies.

Sherlin et al. (2011) pointed out the importance of threshold setting in neurofeedback training, but in many of the neurofeedback studies, the methods, and values for setting the thresholds were not presented (Arns et al., 2014; Egner et al., 2004; Gruzelier, Inoue, Smart, Steed, & Steffert, 2010; Sime, 2004). The rationale and basis for setting the threshold elucidate psychophysiological changes due to a threshold value. However, there is a lack of research in this area. Therefore, this study can be used as a reference for setting thresholds for neurofeedback trainees (Gruzelier, 2014b; Sherlin et al., 2011). Considering the effect of rewards on learning, it is necessary to study the setting of thresholds, which is required for determining the possibility and the frequency of compensation in neurofeedback, and its application. Therefore, in this study, we tried to clarify the relationship between threshold setting and EEG changes (learning).

The outcome of the initial session, which is the starting point of neurofeedback training, is important because it can motivate future training and is the foundation for subsequent treatment plans (Gruzelier et al., 2010; Yoo et al., 2006). The trainee is presented with the results of their initial performance, which helps to increase their motivation to participate (Gruzelier et al., 2010; Yoo et al., 2006). In neurofeedback, it is necessary to plan and implement a protocol so that the subject can receive appropriate compensation in order to control the EEG effectively during the initial session. According to learning psychology, the frequency of compensation affects learning. This is based on a previous study that found that difficult training affects learning (Gottlieb, 2004; Reynolds, 1958; Wagner, 1961). The results of studies related to initial learning support the static correlation between the frequency of rewards and rapid behavior acquisition. Continuous reinforcement is effective in learning, and neurofeedback mainly provides rewards with successive reinforcement schemes (Sherlin et al., 2011; Sulzer et al., 2013).

Shaping, which corresponds to continuous reinforcement in learning psychology, is useful for learning new and difficult behaviors (Konidaris & Barto, 2006). In shaping, actions are progressively performed until participants reach the target behavior, and the criteria for compensation is modified each step. If we apply shaping to neurofeedback, we can use successive approximations to learn the difficult behavior of the EEG control. To learn the difficult behavior of EEG control, we first need to provide compensation even at levels below the target EEG and then raise the standard for providing compensation (Sherlin et al., 2011; Sterman & Egner, 2006).

There are two views on the threshold setting according to shaping. From the trainers' perspective, they have to decide whether to provide the first reward for an easy task or a more difficult task (Miltenberger, 2011). For example, if you want to teach a child how to open a door, you need to define this act by looking at the door or taking a step towards the door. In shaping, an absolute standard act that results in a reward does not exist because the standard will gradually change.

For the trainee, being able to receive a lot of compensation with the easiest behavior is important. In the example above, if you set the first reward level to the easiest level, subjects can get rewarded by just looking at the door. However, if you set the first reward level at taking a step towards the door, the frequency of compensation will be less because it is more difficult than the former example (Miltenberger, 2011).

The control of EEG, which is the target of neurofeedback, is exceedingly difficult for the training subjects because they try to maintain the state of the EEG at higher or lower than average. Therefore, it is possible to effectively apply shaping to neurofeedback in order to perform a new action with a high degree of difficulty.

In this study, the sensory-motor rhythm (SMR; 12–15 Hz) increase protocol was used to determine the effect of threshold setting on neurofeedback training performance. According to a previous study on SMR, Vernon et al. (2003) reported that neurofeedback training was applied to the Cz region, which is a sensory-motor cortex. Perceptual sensitivity and attentional performance were improved. Based on this study, Ros et al. (2009) conducted an SMR protocol for ophthalmology and found positive changes, such as the improvement of overall sealing techniques, shortening of execution time, and a reduction of anxiety. In addition, SMR training was conducted with athletes to improve their performance, skills, and concentration (Xiang, Hou, Liao, Liao, & Hu, 2018). As mentioned above, the SMR protocols have been widely applied.

In this study, different thresholds were set for each group to examine the degree of EEG changes according to the threshold settings. The SMR neurofeedback training was divided into three groups: *low*, *medium*, and *high*, according to the threshold. The low group was less likely to receive compensation, and the high group was more likely to receive compensation. It was expected that the degree of change of SMR EEG in the high probability group would be significantly higher than in the other groups.

Methods

Participants

The subjects of this study were recruited through advertisements on wall posters, the university homepage noticeboard, and social media focused on undergraduate or graduate adults from a college in Seoul city. The participants were screened by a telephone interview which lasted for about 10 minutes. The screening criteria included caffeine intake, smoking, alcohol consumption, medical history, educational background, and handgrip. Excessive caffeine intake can lead to arousal and affect EEGs. People who consumed more caffeine than the recommended daily intake, which is 400 mg of caffeine, were excluded (Hammond, 2003; Okello, Abadi & Abadi, 2016). To collect information related to nicotine and alcohol addiction, questions were asked on their weekly intake frequency and intake amount. People were excluded if they had experienced trauma or had a personal history that could cause neurobiological abnormalities (Good et al., 2001). In the present study, the Edinburgh Handedness Inventory was used to measure right-handedness (Oldfield, 1971). None of the participants had previously experienced neurofeedback training because the results of the initial learning experience were wanted (Rasey, Lubar, McIntyre, Zoffuto, & Abbott, 1995). Among the 90 participants who indicated their willingness to participate by telephone, 64 were selected in the first screening process. The participants that were excluded were due to being left-handed (*n* = 6), taking drugs (*n* = 3), not being able to be reached (*n* = 7), and not being able to speak (*n* = 10).

Clinical interviews were conducted by a clinical psychologist using the structured clinical interview for DSM-IV (SCID-I) to determine whether the first 64 participants were normal without any comorbidities. To control the level of intelligence, the K-WAIS-IV short forms (Choe et al., 2014) were used to exclude participants with an IQ of less than 80 or more than 120. All subjects received a sufficient explanation about the study from the researcher, read and signed the research agreement, participated in the study, and received a participation fee of $21. In the second screening process, a total of eight participants were identified as having a depressive disorder (*n* = 2), sleep disorder (*n* = 1), alcohol abuse (*n* = 1), social phobia (*n* = 1), specific phobia (*n* = 2), or posttraumatic stress disorder (*n* = 1). Finally, a total of 56 participants (12 males and 44 females) qualified for this study.

Ethical Approval

All procedures performed in studies involving human participants were in accordance with the ethical standards of the institutional research committee (IRB) and the 1964 Helsinki Declaration and its later amendments or comparable ethical standards. Informed consent was obtained from all individual participants included in the study.

Assessment Scale

Edinburgh Handedness Inventory. To control the influence of handedness, we used the Edinburgh Handhold Test proposed by Oldfield (1971). The score for each item is left-handed (−10), mainly left-handed (−5), using both hands (0), mainly right-handed (+5), and right-handed (+10). The total score has a distribution of −100 points to +100 points. In this study, only right-handed individuals with more than 50 points were selected.

Structured Clinical Interview for DSM-IV (SCID-I). A structured interview tool based on the DSM-IV diagnostic criteria was conducted to assess mood, anxiety, somatoform, eating, adaptive, selective disorders, and alcohol and other substance use. Any participants with a mental illness were excluded.

Korean version of the Wechsler Adult Intelligence Scale, 4th edition (K-WAIS-IV). The Korean version of the Wechsler Adult Intelligence Scale (4th edition) measures various cognitive functions. People with an IQ of 80 or lower are considered to have a borderline intellectual disability or an intellectual disability (American Psychiatric Association, 2000). Those with an IQ of less than 80 were excluded due to concerns that the neurofeedback training would not be effective in the time allowed.

Beck Depression Inventory (BDI). The Beck Depression Inventory (BDI) was used to measure the degree of depression by self-report. The degree of subjective depression can affect training even though it is not enough to clinically satisfy the diagnostic criteria of a depressive disorder. The BDI is a questionnaire that consists of 21 items and measures the severity of depression. The score ranges from 0 to 63. If the score is 16 or more, intervention for depressive symptoms is required.

Beck Anxiety Inventory (BAI). The Beck Anxiety Inventory was used to measure the severity of anxiety.

The BAI scores of participants were set as a control variable, as it was judged that subjective anxiety would affect the training. A total of 21 items are included on a Likert 4-point scale. If the total score is 22 or greater, observation and intervention for anxiety are required.

Procedure

EEG. ProComp5 Infiniti (Thought Technology Ltd., Montreal, Canada) was used as a neurofeedback training device, and BioGraph Infiniti (Thought Technology Ltd., Montreal, Canada) version 5.1.2 was used as the training program. The EEG signals measured during the training ranged from 1 Hz to 60 Hz through the Infiniti Impulse Response (IIR) filter, and the sampling rate was 256 Hz. Next, fast Fourier transform (FFT) was performed to calculate delta (1–4 Hz), theta (4–8 Hz), alpha (8–12 Hz), beta1; and the frequency bands of SMR (12–15 Hz), beta2 (15–18 Hz), beta3 (18–25 Hz), beta4 (25–30 Hz), and gamma (30–60 Hz). Artifacts are recorded activity that are not of cerebral origin and include eye and muscle movements. In the study by Barea, Boquete, Mazo, and López (2002), the signal changed by about 20 μV every time the eye moved. Removing the artifacts based on a criterion of ± 25 μV can eliminate signals such as body movement and blinking. Since the rejection threshold standard that trainers often use is ± 25 μV, physical channel rejection of auto-rejection was set to 25, thereby removing any artifacts in this study (Frank, Thought Technology Ltd, personal communication, March 17, 2016). The EEG data was collected in the Cz region according to the 10–20 international electrode arrangement, and the reference and ground electrodes were attached to both ear lobes, A1, and A2 (Figure 1).

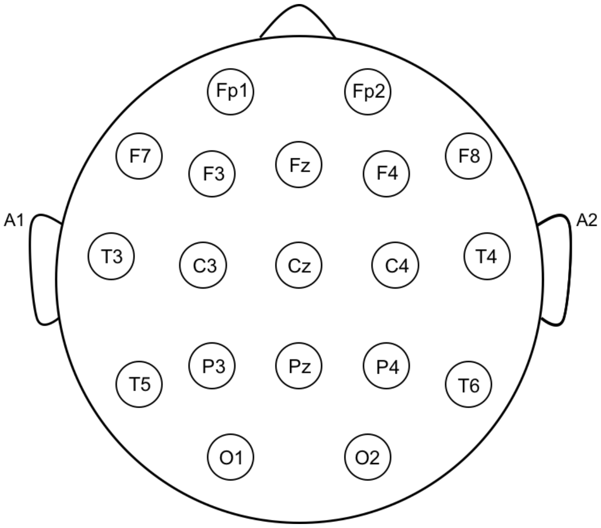

Figure 1. International 10–20 electrode system.

Neurofeedback training. The training took place between December 2015 and October 2016, from 12 p.m. to 6 p.m. Participants were instructed to sleep sufficiently before visiting the laboratory and not to consume caffeinated beverages 24 hours prior to training.

The training session included equipment attachment, training, and equipment removal, which took approximately 60 minutes. Training was conducted in a shielded room in the laboratory where the noise was blocked, and metal products, including earrings, necklaces, and watches, were not to be in or on the body in the shielded room.

We provided time for participants to adapt to the unfamiliar laboratory environment before the training and explained the procedure. Training consisted of four 10-min sessions. The EEG data from the baseline was measured for 5 min, and data from the training session (first, second, third, and fourth blocks) was measured for 10 min. In addition, the posttraining EEG was measured for 5 min. The baseline block measured the baseline EEG without any visual or auditory stimuli. The post block, like the baseline block, did not any have visual or auditory stimuli but attempted to control the EEG. Posttraining EEG was used to determine whether the subject learned how to control brain wave activity during four blocks of neurofeedback training (10 min per block). Based on the mean EEG values collected at baseline, we set different thresholds according to the group. During the training, participants were asked not to move and not to deliberately have positive thoughts or imagery such as imagining a mountain or peaceful scene (Bashashati, Ward, Birch, Hashemi, & Khalilzadeh, 2003; Jindal, 2013). During all measurements and training, participants were instructed to minimize head and body movements. Between the blocks, participants took a 1- to 2-minute break to rest their eyes and relax their muscles. The SMR (12–15 Hz) increase protocol was used as the neurofeedback protocol, and the training aimed to increase the SMR and suppress theta (4–8 Hz) and high beta (25–30 Hz; Cortoos et al., 2010). Each frequency band was presented as a bar graph, and the color of the graph showed the performance of each participant. When the participant performed well, the color of the graph turned to green. Contrastingly, when the participant did not focus on the training, the graph turned red (SMR: keep above the threshold, theta, high beta: keep below threshold). In addition, when the training was going well, the trainee could see that a piece of the puzzle slotted into place on the screen with a ringing sound, functioning as visual and auditory feedback, respectively.

Threshold setting. To see the difference in training according to the experimental purpose, the frequency of rewards was set differently for the three groups, as were the thresholds. For the threshold setting, a multiplicative method was used to maintain a constant reinforcement rate. This solves the problem of being compensated even when the level of performance falls, which is a limitation of the method of obtaining percentage compensation regardless of performance (Arns et al., 2014; Egner et al., 2004; Ros et al., 2009).

Triangular wave. The values of the multiple that multiply the average EEG in the low, medium, and high groups were deduced based on the trigonometric function and Fourier theorem, which can be applied to periodic waveforms, such as seismic, sound, and brain waves (Shaker, 2007). Compensation differences according to the threshold setting are divided into three levels: low, medium, and high. The low group set the threshold based on 30%, which was set in a previous study (Egner et al., 2004; Ros et al., 2009). Theta, SMR, and high beta graphs corresponding to the SMR protocol must be trained at the same time to satisfy the conditions, and it is expected that the enhancement will be substantially lower than 30%. The medium group had a threshold set for compensation similar at 50%, and the high group at 80% or higher when satisfying the three graphs.

Statistical analysis. To evaluate the effectiveness of training, baseline, 1 block, and post block EEGs were analyzed after eliminating artifacts, and the average amplitude of each frequency band was calculated. Data were analyzed using SPSS (Statistical Package for Social Science) version 21.0, and nonparametric tests were used because the data was not normally distributed. The Chi-square and Kruskal-Wallis tests were performed to verify the homogeneity of the demographic variables in each group. The demographic data included sex, age, education duration, grip, and IQ. The Kruskal-Wallis test was used to compare BDI and BAI scores between the groups, and the homogeneity of the baseline waves was verified. The Wilcoxon signed-rank test was performed to compare each group's EEG during neurofeedback and postneurofeedback training.

Results

Demographic and Pretraining Variables

The study sample consisted of 56 participants: Low group 19 (*M* = 3, *F* = 16), Medium group 17 (*M* = 4, *F* = 13), and High group 20 (*M* = 5, *F* = 15). The Chi-square and Kruskal-Wallis tests showed no significant differences in the demographic variables (Table 1).

Table 1

Demographic and pretraining variables

	Low (*n* = 19)	Medium (*n* = 17)	High (*n* = 20)	x^2	*p*-value
Sex	M = 3, F = 16	M = 4, F = 13	M = 5, F = 15	0.56	.76
	M(*SD*)	*M*(*SD*)	*M*(*SD*)		
Age	22.11(2.16)	23.06(2.11)	22.70(2.83)	1.33	.51
Education	14.68(1.00)	14.65(1.22)	14.60(1.23)	0.03	.99
Handgrip	61.79(34.02)	59.03(38.24)	62.00(37.92)	0.47	.79
IQ	105.57(8.41)	100.84(7.39)	106.89(9.05)	4.65	.10
BDI	9.84(8.49)	9.12(6.35)	9.70(6.35)	0.52	.77
BAI	6.74(6.54)	6.29(6.48)	3.55(3.17)	2.16	.34

Note. Handgrip: Edinburgh Handedness Inventory; IQ: K-WAIS-IV short forms; BDI: Beck Depression Inventory; BAI: Beck Anxiety Inventory.

Comparison of EEG Changes

The Kruskal-Wallis test showed no differences between the groups in baseline EEG, which means that the neurofeedback training was performed under the same conditions (Table 2).

A Wilcoxon signed-rank test was performed between the mean SMR in 1 block and the post block SMR with all participants to verify the increased SMR level due to neurofeedback training. As a result, it was found that the SMR value had increased significantly ($z(56) = -2.317$, $p = .021$). To validate the effect of neurofeedback training on the EEG, a Wilcoxon signed-rank test was performed between 1 block and post block for each group. The mean EEG values of the SMR were analyzed as follows (Table 3).

There was a statistically significant increase in SMR between 1 block and the post block ($z = -2.39$, $p < .05$) in the high-frequency group, while there was no difference in the SMR between the low and medium groups. Theta and high beta values are suppressed so that they do not rise. As a result of the analysis of 1 block and post block EEG, there were no statistically significant decreases or increases (Table 4).

Table 2

Baseline EEG by group

	Low *M*(*SD*)	Medium *M*(*SD*)	High *M*(*SD*)	x^2	*p*-value
SMR (12–15 Hz)	4.56(1.23)	4.29(0.72)	4.55(1.30)	0.90	.64
Theta (4–8 Hz)	9.13(1.40)	9.04(1.38)	8.48(1.28)	2.06	.36
High Beta (26–30 Hz)	3.18(0.63)	3.14(0.55)	3.36(0.92)	0.86	.65

Table 3

Comparison of the SMR changes

	Group	1 block	Post block	1 block – Post block	
		M(*SD*)	*M*(*SD*)	*z*	*p*-value
SMR	Low	3.96(0.99)	3.95(0.87)	−0.89	.376
	Medium	4.01(0.66)	4.09(0.78)	−0.73	.463
	High	4.12(1.29)	4.39(1.20)	−2.39	**.017***

*$p < .05$

Table 4

Theta, and High Beta changes

	Group	1 block – Post block			Group	1 block – Post block	
		z	*p*-value			*z*	*p*-value
Theta	Low	−0.161	.872	High Beta	Low	−1.067	.286
	Medium	−0.118	.906		Medium	−1.349	.177
	High	−0.112	.911		High	−0.747	.455

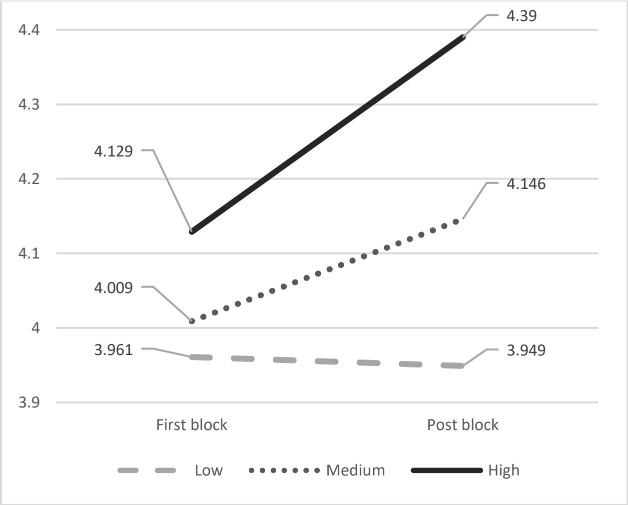

Figure 2. Mean value change of SMR by block.

Discussion

This study aimed to investigate whether the reward difficulty, according to the threshold setting, affects the changes in EEG (learning) in neurofeedback. The frequency of rewards varies based on the threshold setting, and the settings were divided into three groups: low, medium, and high. The aim was to determine if there was a significant difference in the EEG changes between the three groups. The baseline measurement used for setting the threshold was done without any intentional effort to change the EEG. However, the postmeasurement assessment measures the intuitively learned methods that could be compensated in the past training. Therefore, the baseline condition and the postcondition are not identical, and thus cannot be compared. In other words, post block and 1 block are under the same condition, and it is a criterion to analyze the degree of fluctuation of EEG in training sessions.

As a main result of the research, the SMR protocol showed that the mean value of SMR increased in the post block compared to the 1 block and that EEG significantly increased through the neurofeedback protocol. In addition, only the high group, which is more likely to receive compensation, showed a more significant increase in EEG in the post block compared to the 1 block in the training session. In particular, the SMR increase in the post block compared to the SMR in the training block suggests that frequent compensation helps to increase SMR during training, which is consistent with the principle of compensation (Sherlin et al., 2011). In the medium and low groups, it was difficult to receive compensation, and the frequency of compensation was lower. This is consistent with the results of previous studies. According to Wagner's (1961) study, mice that received more frequent rewards from the first session to the fourth session reached the destination faster than the other groups. In addition, mice that received continuous reinforcement (100%) were faster than those with intermittent reinforcement (50%). Gottlieb (2004) and Reynolds (1958) also found that the successive reinforcement group was faster in the early sessions than the intermittent reinforcement group.

The mean EEG did not increase gradually as the 1 to 4 blocks progressed. The results are similar to those of previous studies in which EEG changes were not statistically significant during training (Ros et al., 2013). Fatigue, concentration, and stress are some of the reasons why EEG does not rise gradually (Young et al., 2014). Also, it seems that neurofeedback training should be intuitively learned, and it is challenging to see a significant increase over such a short period. In this study, the increase in SMR in the post block was higher in the stable state compared to 1 block, which are situations where visual and auditory stimuli were given, and training was needed. This means that SMR can increase in a stable state after going through a method learned during training.

The implications of this study are as follows: first, although neurofeedback claims to be based on the principle of learning psychology, there are few studies on the frequency of threshold setting and compensation. This study was meaningful because initial experiments were conducted to clarify the relationship between thresholds set and EEG changes. The above results suggest that the initial training for neurofeedback should set a threshold value for easy compensation. That is, in setting the threshold, the difficulty level of the training should be set low so that the subject can receive frequent compensation during the initial session.

Second, discussions regarding sessions are continuing. The trainer should provide the client with a therapeutic effect in the minimum amount of time possible as the longer times, increase the chance of withdrawal. Additionally, trainers should reduce the number of sessions required due to costs (Arnold et al., 2012; Simkin, Thatcher, & Lubar, 2014). However, this needs to be carefully done. To lower the number of sessions, a threshold value can be set low so that compensation can be easily received, thus changing EEG from the initial session. This could also be a way to prevent motivational decline due to the absence of effective EEG changes in the early sessions.

Limitations

The ultimate goal of neurofeedback is to help subjects control their brain waves (Hammond, 2011). This study shows that a lower threshold value can be effective as compensation can be easily received in the initial phase. However, it is not known whether it is effective for mid-term training or generalization. Further studies are needed to establish thresholds for long-term sessions. In the psychology of learning, it is found that the frequency of intermittent compensation is effective in the latter part of learning, and it can be expected that intermittent compensation is more effective in mid-term training. Based on the learning theory, it can be suggested that it would be effective to set a threshold value to facilitate the changes of target EEG with low difficulty (frequent frequency) at the beginning of training, and then to set a threshold value to the lower frequency as training progresses.

Early studies on the frequency of threshold setting and compensation were conducted in this study, and the amount of compensation among the factors involved in learning was also known to be a factor. In the psychology of learning, the amount of food is usually used to increase the amount of compensation (Wagner, 1961). On the other hand, it is difficult to control the amount of visual and auditory compensation as a reward for neurofeedback. Changing the amount of compensation may provide multiple visual stimuli, rather than providing a single visual stimulus. The number of rewards can vary the type of visual reward presented, and in the case of auditory rewards, the amount is even more challenging to control. Further research is needed to investigate whether the provision of multiple visual stimuli affects the subject.

Visual and auditory compensation was provided with feedback during training. In learning psychology, unconditional reinforcers (primary reinforcement), candy, and sweets have been used for children, and food has been mainly used for animals (Miltenberger, 2011). In neurofeedback, a secondary reinforcer such as sound, graph, visual feedback (space flight, ball rolling) was used (Sterman & Egner, 2006). The reward that was used in this study during the training session may have worked as a reinforcer. The feedback used in neurofeedback is usually the same as a conditional reinforcer (praise reinforcement). In this study, the subjects were told that ”sound and visual changes occur with feedback when they are doing well.” Further research is needed on the types of reinforcers that are effective in neurofeedback. The visual and auditory compensation used in this study means “successful” and “good,” so they were used in terms of positive reinforcement and compensation for the desired action.

Finally, participants were generally in their early 20s, with a period of education over 14 years. Therefore, the findings of the current study may not be able to be generalized for children, the elderly, and specific clinical groups.

Conclusion

This study investigated different threshold setting methods. Initially, it was shown that the threshold value set for easy compensation was effective for learning (change in EEG). Based on these results, it is expected that neurofeedback trainers will be able to set threshold values, and neurofeedback training will be able to be performed more efficiently.

Author Disclosures

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NeuroRegulation

The Clinical Outcome of Concurrent Speech Therapy and Transcranial Direct Current Stimulation in Dysarthria and Palilalia Following Traumatic Brain Injury: A Case Study

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Abstract

Introduction: Dysarthria, a neurological motor speech disorder, is regarded as a common sequala of traumatic brain injury (TBI). Palilalia is a speech disorder characterized by involuntary repetition of words, phrases, or sentences. Based on the evidence supporting the effectiveness of transcranial direct current stimulation (tDCS) in some speech disorders, we hypothesized that using tDCS would enhance the expected speech therapy outcome in a case of TBI with dysarthria and palilalia. **Method:** The "Be Clear" protocol, a relatively new approach in speech therapy in dysarthria, together with tDCS were employed in this single case investigation. With respect to the tDCS montage, regions of interest (ROIs) were identified based on the comparative analysis of resting-state vs. speech task-concurrent qEEG results. **Results:** Measures of intelligibility, an important index in the assessment of dysarthria, were superior to the primary protocol results immediately and 4 months after intervention. We did not find any factor other than the use of tDCS to justify this superiority. Palilalia showed a remarkable improvement immediately after intervention but fell somewhat after 4 months. This might have been justified owing to the subcortical origin of palilalia. **Conclusion:** Our present findings suggested that applying tDCS together with speech therapy might be more effective in similar case profiles as compared to traditional speech therapy. This notion needs to be systematically investigated in well-designed parallel arm clinical trials.

Keywords: traumatic brain injury (TBI); dysarthria; palilalia; transcranial direct current stimulation (tDCS); qEEG; speech therapy

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Introduction

Traumatic brain injury (TBI) often results in significant neurofunctional deficits and/or evidence of brain pathology caused by an external force (Menon, Schwab, Wright, & Maas, 2010). According to a local observational research (2007–2008), the incidence of TBI was estimated at 53.3–144 per 100,000 in Tehran (Rahimi-Movaghar, Saadat, Rasouli, Ghahramani, & Eghbali, 2011).

TBI potentially leaves patients with consequences in physical, sensory, cognitive, communicative, swallowing, and behavioral domains (ASHA, 2017). High-level cognitive functions, psychiatric disorders, and impairment of social and leisure activities are among long-term consequences of TBI (Stocchetti & Zanier, 2016).

Along these lines, dysarthria is a communicative deficit regarded as one of the consequences of TBI. The condition is an acquired speech disorder which occurs following neurological injury of the motor component of the speech circuitry characterized by reducing the speech intelligibility due to poor, inaccurate, slow, or uncoordinated speech muscles (Mitchell, Bowen, Tyson, Butterfint, & Conroy, 2017). This may possibly affect speech-related functions including respiratory, articulation, phonation, and resonance mechanisms (Kwon, Do, Park, Chang, & Chun, 2015).

The mainstay of behavioral treatment in cases with stable dysarthria remains to be speech therapy which is yet a time-consuming procedure with relative outcomes (Mitchell et al., 2017). Speech therapy may focus on enhancement of particular speech subsystem through strengthening orobuccal musculature, implementing behavioral changes such as decreasing speaking rate and accurate pronunciation of speech phonemes by focusing on the kinetic, kinematic, and somatosensory aspects of speech production to improve intelligibility (Robertson, 2001; Yorkston, Hakel, Beukelman, & Fager, 2007) or providing assistive devices to enhance communicative interactions (Yakcoub, Selouani, & O'Shaughnessy, 2008).

Researchers have recently developed a program named “Be Clear” comprising a treatment plan based on Principles of Motor Learning (PML) which is a relatively new approach in treating motor disorders and believed to facilitate retention and transfer of skilled movement (Maas et al., 2008). The program is typically scheduled for 16 one-hour sessions and 15 minutes of homework over 4 weeks. Unlike traditional approaches, the program is based on external attentional focus (instead of internal attentional focus), intensive treatment, and practice schedule emphasizing on meaningful speech production tasks (Park, Theodoros, Finch, & Cardell, 2016). Park et al. examined cases with dysarthria and deteriorating sentence intelligibility following TBI. In their prospective evaluation, they considered decreasing in speech rate as one of the most relevant correlates of treatment outcome just immediately and 3 months after the intervention (Park et al., 2016). Meanwhile, no significant improvement was observed in terms of word intelligibility and psychosocial impact of dysarthria from the perspective of the speaker (Park et al., 2016).

Although the incidence of dysarthria following TBI is estimated at almost 60% (Mitchell et al., 2017), to date, there are few investigations on neurorehabilitation approaches using the concurrent use of electrical or magnetic brain stimulation and speech therapy. To our best knowledge, the effectiveness of such techniques in TBI-induced dysarthria has similarly not been articulated. As such, further research is required to examine the effectiveness of these approaches associated with common behavioral treatments given the high incidence of TBI as well as sever communicative problems in TBI patients who suffer from dysarthria.

Palilalia is a type of motor perseveration involving speech, consisting of compulsive repetition of normally articulated phrases, words, or syllables often with increasing rapidity and decreasing volume. Palilalia has been described in several neurological disorders such as cerebrovascular and degenerative diseases, encephalitis or tic disorders (Landi et al., 2012). Basal ganglia involvement has been suggested as the culprit in some cases of palilalia. Palilalia can be seen in untreated schizophrenic patients, in paramedian thalamic damage, also in advanced stages of degenerative brain diseases such as Alzheimer's disease, and in cerebrovascular or traumatic lesions of the basal ganglia (Azevedo et al., 2012; Van Borsel, Bontinck, Coryn, Paemeleire, & Vandemaele, 2007) which the latter case is likely to be about our case.

Transcranial direct current stimulation (tDCS) is a noninvasive procedure in which brain cortices get potentiated for depolarization by an electrical field with a maximum 2 milliampere (mA) direct current and electrodes localized on definite area over the scalp. The effectiveness of using tDCS in chronic motor disorders (Chang, Choi, & Tseng, 2017), dysarthria (You, Chun, Kim, Han, & Jung, 2010), and language impairments (Devido-Santos et al., 2013) due to stroke has been substantiated through brain imaging (Stagg & Johansen-Berg, 2013). In various conditions including memory problems, executive dysfunctions, as well as issues with cognitive agility in chronic and subacute conditions in TBI, tDCS has been successfully applied (Demirtas-Tatlidede, Vahabzadeh-Hagh, Bernabeu, Tormos, & Pascual-Leone, 2012). According to a systematic review, common protocols of tDCS have not associated with serious and irreversible side effects across over 33,200 sessions in 1000 subjects who underwent repeated sessions (Bikson et al., 2016).

The montage of tDCS electrodes is based on related study findings or neuroimaging techniques such as functional magnetic resonance imaging (fMRI), positron emission tomography (PET), or electroencephalography (EEG). EEG is a method to record and measure brain's electrical activity. Electrical brain signals or electroencephalogram contained regular patterns that may be better understood by their common spatial patterns (i.e., frequency range and amplitude). Bursts of sinusoidal waves occurred and reoccurred in a predictable fashion are corresponded with mental states. Indeed, today's advances in computer science and artificial intelligence have paved the way for new and faster analytical methods in digitally recorded signals, determining specific patterns in signals, and saving the digital data. Quantitative EEG (qEEG) is then a powerful and sensitive tool for identifying maladaptive brain activity patterns (Kaiser, 2007).

Based on the above, we hypothesized that a qEEG-informed tDCS intervention could potentially enhance the effectiveness of speech therapy in a client with chronic dysarthria following TBI. To test the hypothesis at least in a single case investigation, we applied the constructs of the Be Clear protocol in dysarthria together with tDCS. As such, an individualized therapy plan was formulated in Persian and applied to the patient. Because of the strong relationship between information transfer and speech intelligibility in dysarthria (Beukelman & Yorkston, 1979), this measure was applied as a primary index in speech assessment. In summary, the findings of the current study revealed tES concurrent with speech therapy could yield more effectiveness compared to the standard practice of speech therapy in cases with TBI. This may then be regarded as a promising treatment plan in TBI-related language problems in the future. An overview of diagnostic and therapeutic procedures is illustrated in Diagram 1.

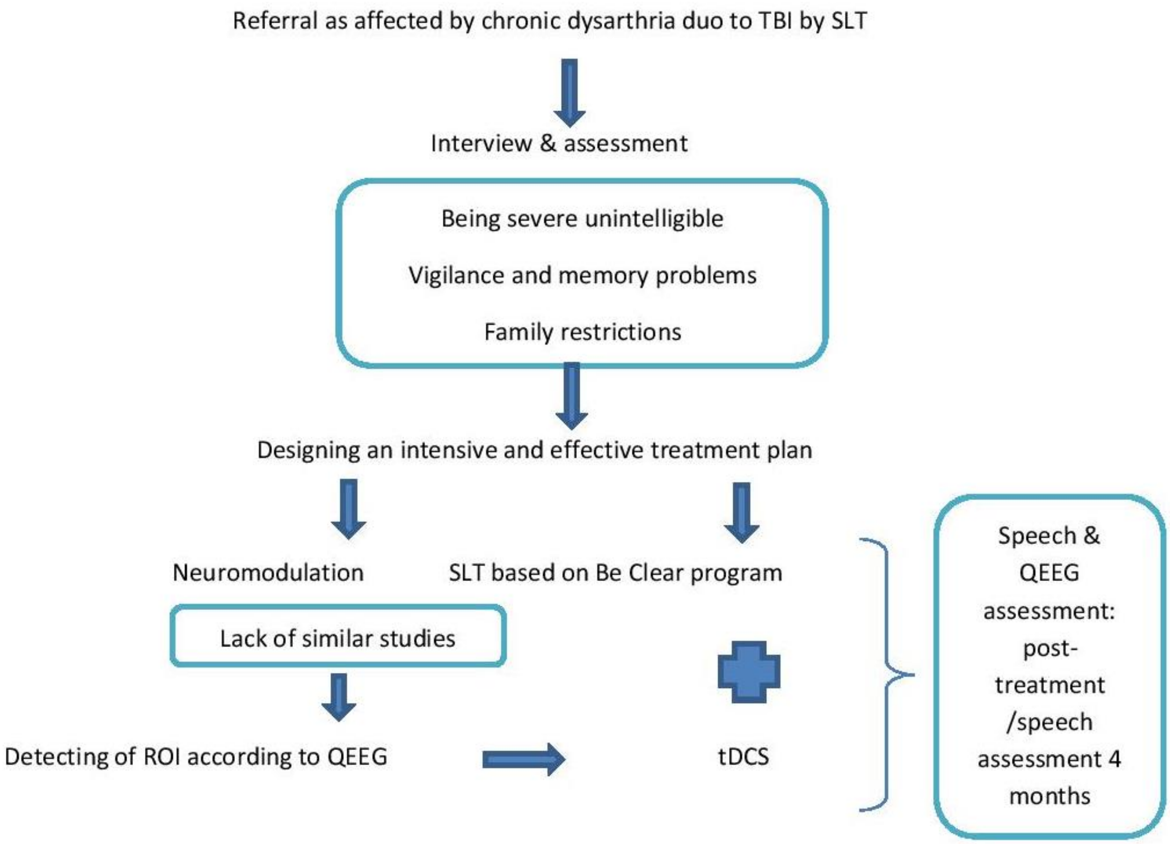

Diagram 1. Flow chart of the study.

Methods

Case Presentation

MA was a 40-year-old male who had a car crash 5 years prior to presentation and experienced a closed head injury resulting in hospitalization, whereby he survived 31 days in a coma during his ICU admission. The patient had a master's degree in geology and used to work in a state-owned company prior to the accident. He was diagnosed with diffused axonal injury in his course of admission. The case had lost his orientation, movement, speech, and efficient swallowing for 6 months after which started to gradually regain some functions following intensive rehabilitation. The case was referred as dysarthria following TBI because of no progress through traditional speech therapy over last 3 years by his speech language therapist.

Informed consent was obtained for each experiment. All procedures related to the present investigation were approved by the Ethics Committee of Shiraz University of Medical Sciences (IR.SUMS.REC.1397.799).

Following the initial assessments by a clinical neuroscientist and speech language pathologist, he was found to have mild left-sided hemiparesis, left mild facial paresis and oral apraxia, decreased frequency and amplitude of oral movements, hypoesthesia in left upper extremity, slight gait paresis, and left upper extremity hyperreflexia. There was no hearing problem in his history as well as our observation.

Speech problems. The patient had significant communication problem where unintelligibility was the chief complaint. The family was deeply concerned about his excessive repetition of his own words and sentences in conversations.

Cognitive problems. He was found to have notable problem in short-term and episodic memory upon cognitive profile that had potentially caused difficulty in his social functions. Apparently, he was unable to recall what the breakfast was or how he came to our Brain Laboratory on the day of initial assessment.

Diagnostic Assessments and Interventions

Speech and language assessments. According to our speech language pathologist (SLP), the case was diagnosed with spastic dysarthria. Speech intelligibility index, diadochokinetic rate, maximum phonation time, speech rate, and the percentage of repeated words in all words were calculated. Strained and struggled phonation in open vowels and back consonants were diagnosed upon perceptual analyses.

For the assessment of intelligibility, as per the Be Clear protocol, eight conversational speech samples (approximately 40 seconds), presented in four paired comparisons, on topics of the participant's professional interests were given. The outcome was rated by four native Persian listeners in terms of clarity or understandability. The speech samples were randomly presented to listeners in several different combinations including (1) pretreatment/posttreatment, (2) pretreatment/follow-up, (3) posttreatment/pretreatment, and (4) follow-up/pretreatment. The listeners' task was to determine whether the first or the second sample of each pair was easier to understand, or whether there was no discernible difference. Listeners were blinded to the assessment intervals (i.e., pretreatment, posttreatment, follow-up) and had no confrontation with the dysarthric speech. They were 25–45 years old and have undergraduate degrees (their email address is available for further correspondence). Prior to task completion, the listeners were provided with the following instructions adopted from the Be Clear protocol (Park et al., 2016):

> You are going to hear pairs of audio speech samples. You will be deciding which speech sample, the first or the second, is clearer or easier to understand. On your paper you will write the name of a sample is easier to understand. If you do not think there is any difference in how easy it is to understand the two samples, write the word same. Repeat this procedure after one week and date it. There is a training sample at the first to listen and judge (Park et al., 2016).

Each listener completed the ratings twice with a 1-week interval. A total of 32 ratings comparing the pretreatment and posttreatment/follow-up speech samples were also included in the analysis.

Speech intelligibility is of basic considerations in dysarthria intervention (Hustad, 2006) and some objective methods have been suggested for its measurement. Of basic objective measurement methods is transcription the words of speakers' sentences by the listeners and then dividing the words correctly discriminated by whole words. The percentage of intelligibility is obtained by multiplying the result by 100 (Miller, 2013). Formal assessment of intelligibility was accomplished with Assessment of Intelligibility of Dysarthric Speech (ASSIDS)

(Yorkston, Beukelman, & Traynor, 1984) in the Be Clear program. The subjects are required to repeat a list of words and sentences after examiner and percentage of intelligibility is estimated in ASSIDS by transcription of speakers' responses. There is no such reliable test in Persian, so six samples of paired comparisons, two samples from each stage, were randomly chosen and transcribed by two independent SLPs. Then, the SLP calculated the percentage of words which were correctly transcribed. The final estimation was confirmed by the independent SLPs. In addition, the rate of speech was extracted in the same way. As the sample extraction method had to be consistent throughout the investigation (Miller, 2013), the content of participant's monologues which were about his professional major (geology) were recorded in the presence of a listener and the project SLP by a voice recorder Android software 1 m from his mouth and samples with 30–46 seconds connected speech with a coherent topic were selected and delivered to independent listeners for perceptual analyses and objective measurements.

The set of speech assessments adopted from the Be Clear protocol was carried out just before and after interventions as well as 4 months after interventions to assess dysarthria. The index of repeated words was applied to assess palilalia. The percentage of repeated words in whole words characterizing palilalia was calculated in speech samples by the main SLP based on independent SLTs' transcriptions.

Diadochokinetic rate (DDR) and maximum phonation time (MPT) were evaluated by independent SLPs besides the items stated in main protocol since these two aspects are affected in dysarthria (Kwon et al., 2015; Mitchell et al., 2017; Portnoy & Aronson, 1982). DDR, which is also known as alternative motion rate, is an index used in clinical neurology and speech and language pathology to assess orofacial function and speech motor control and could be an indicator for rehabilitation efficacy (Yang, Chung, Chi, Chen, & Wang, 2011). The rate is estimated by repetition of some nonsense syllables (/pe/, /te/, /ke/, each one 20 times, and /pe,te,ke/ 10 times) as fast as possible and dividing the number by the times which is known as Fletcher test (Fletcher, 1972).

Respiration is another affected aspect in dysarthria since reduction or alteration in respiratory support influences the airstream needed for phonation and articulation (Speyer et al., 2010). The maximum phonation time is proven to be a noninvasive, economical, and highly reliable evaluation in voice assessment and provides an objective measure indicating respiratory system efficacy through phonation (Speyer et al., 2010). Subjects are required to sustain a vowel after a deep inhalation for as long as possible at a comfortable pitch and loudness on one exhalation, without straining in this evaluation. The recorded samples during three stages of the study were submitted to independent SLPs to record the time in seconds up to two decimal places. Three subsequent trials were averaged to yield an estimation.

Aphasia was ruled-out based on Persian Aphasia Battery (PAB) developed by Nilipour (Nilipour, Pour Shahbaz, Ghoreishi, & Yousefi, 2016). There were no resonance problems according to our SLP.

Electrophysiological assessments and tDCS application. Since there was no research on the use of tDCS in dysarthria following TBI, regions of interest (ROIs) were identified based on deviant brain electrophysiological patterns in speech tasks and resting-state qEEG compared with normal expected patterns. The EEG data was recorded from 19-channel NRsign amplifier according to the international 10–20 system. The impedance in the plug-in was set to a maximum of 5 KΩ. Data acquisition was performed at a frequency of at least 0.5 and a maximum of 40 Hz, and the sensitivity was adjusted to 70 Hz. An in-built NrSign and NeuroGuide software packages (NrSign, BC, Canada, 2011, and Applied Neuroscience Inc., 2017, respectively) were employed for data analysis.

EEG data was recorded in two conditions—upon resting eyes-open state and while performing speech tasks (reading, monologue, and orofacial movements). A minimum of 5 minutes of continuous signal was recorded. Signals were recorded while the participant was sitting on a comfortable chair.

Based on the discretion of two clinical neuroscientists, the therapy was planned using an individualized dual-channel montage for tES. A 2-mA anodal current was applied on F7 and T5 areas (based on the 10–20 system), while the cathod electrodes were placed over F6 and T4 areas during speech therapy sessions (Figure 1). A calibrated DC-stimulator delivered tDCS (Neurostim-2, Medina Teb Ltd, Tehran). The electrode pads (35x35 mm) were covered by equisized sponges soaked with 0.9% saline solution. 19-channel qEEG signals were acquired and analyzed upon speech tasks immediately after intervention. Results have been illustrated in Figure 2.

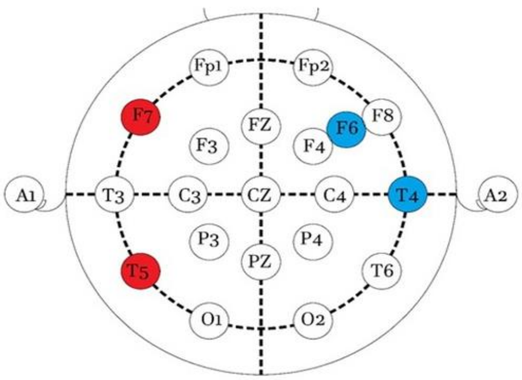

Figure 1. Regions of interest for tDCS. Red: Anodal tDCS, Blue: Cathodal tDCS.

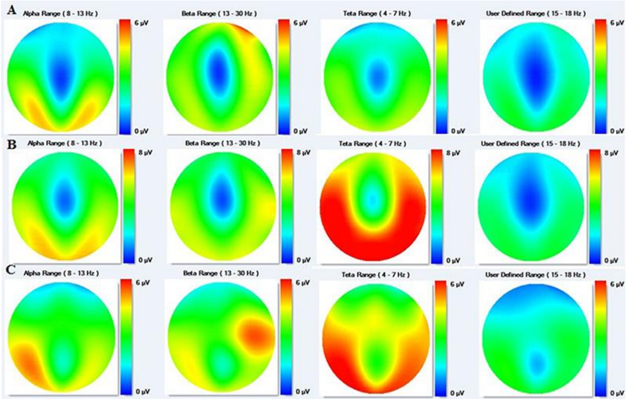

Figure 2. The color-coded qEEG brain map. A) Resting state: focal slowing at P3, P4, T8, T6, and C2 favoring nonspecific brain dysfunction, B) upon speech tasks preintervention: high amplitude for theta frequency in bilateral centrotemporal as well as bioccipital brain regions, C) upon speech tasks postintervention: increasing power of beta range frequency in right centrotemporal.

Behavioral intervention based on Be Clear protocol. The plan of speech therapy was developed in Persian based on the Be Clear protocol with regard to the participant's needs and performed in 10 consecutive 45-min sessions over a 2-week period (5 days a week at 11:00 am) concurrently with tDCS. Since the treatment design was not language dependent, we translated the instructions of the protocol and customized it based on our participant's issues while clinging to instructions. The treatment comprised two phases including a prepractice and an intensive practice phase. All treatment sessions were delivered by the SLP in a one-to-one setting. The 1-hour prepractice phase aimed to establish the subject's understanding about the concept of clear speech production. Speech models were produced in two forms of normal and exaggerated more intelligible articulation by the SLP. The participant was asked to identify which of the speech samples were clearest and then discuss the changes made by the SLP (e.g., speech rate reduction, exaggerated articulation, and no repetition of words and phrases) which might have reflected in the observed improvements in speech clarity.

The knowledge of performance (KP) feedback on the client's speaking technique (e.g., speaking with open mouth, controlling the speech rate using fingers, and soft contact of vocal folds to reduce strained/struggled voice due to dysarthria) was provided in this session to shape a clearer speech. Clear speech refers to a speaking style where individuals spontaneously modify their habitual speech to enhance intelligibility to the listener (Park et al., 2016). The intensive practice phase followed the prepractice phase and consisted of 45-min therapy sessions, five times a week, for 2 weeks. Every session of this phase was initialized with providing an appropriate model and KP feedback by the SLP to shape proper speech through structured speech drills once he was able to produce adequate clarity (Ludlow et al., 2008).

Later during the sessions and consistent with the original protocol, the Be Clear program, reading, picture description, and conversation were delivered in small blocks of trials since PML-based small blocks of trials were expected to result in superior retention and transfer of trained skills than either traditional blocked or random practice schedules (Park et al., 2016).

During the intensive practice sessions, treatment stimuli were created on the basis of participant's interests and functional needs. The specific practice of meaningful speech production tasks was ensured to conform with the principles of specificity and saliency, potentially enhancing the effects of treatment on neuroplasticity (Wulf, 2013). Complete clarity during performing all tasks was ensured by encouraging the participant to focus on his acoustic speech features. The participant was asked to evaluate his speech to improve self-evaluation skills. During the practice phase of each session, the clinician provided general knowledge of results (KR) feedback on speech clarity, labeling speech attempts as either clear or unclear since according to PML an external attentional focus (attentional focus on the external signals following a movement) promotes automaticity, retention, and transfer the outcomes (Hustad, Dardis, & Mccourt, 2007). According to the Be Clear protocol, the latter part of the intensive phase focused on fulfilling homework which was not accomplished because of the mentioned problems.

A part of the present investigation was designed to assess the participant's palilalia given the family concerns. Due to the rare occurrence of such a speech disorder, many specific characteristics of palilalia are yet unknown (Akbari & Shollenbarger, 2016). Therefore, we planned an intervention program based on PML principles. Given the SLP's diagnosis of palilalia in the present case, in intensive practice phase, the participant was required to provide feedback based on his acoustic speech features (based on external attentional focus rule in PML) if there were repetitions. Then he had to discriminate the words which had been repeated and number of repetitions in upon his practice of productive speech.

Results

Speech Analyses

Results of the perceptual analyses of speech intelligibility were compared with normative outcome (Table 1) as per the Be Clear program, developed by Park and colleagues (Park et al., 2016).

Table 1

Results of comparative ratings for speech intelligibility.

	Pre better (%)	Post better (%)	FU better (%)	Same (%)
Current study	0	46.875	46.875	6.0
Original study	14.6	36.500	33.300	15.6

Note. FU corresponds to samples of follow-up assessment, PR to samples of pretreatment assessment, and PT to samples of immediately posttreatment assessment. Pre: pretreatment; post: posttreatment; FU: follow-up.

The paired comparison ratings of speech intelligibility reported from the Be Clear program, for better illustration, was averaged for six participants who experienced dysarthria following TBI and presented in terms of percentage. Posttreatment and follow-up speech samples were rated better than pretreatment,10% and 13% more than the Be Clear program, respectively.

The posttreatment and follow-up intelligibility gain in the Be Clear program was 8.36 and 6.99, whereas they were 38.3 and 24.7 in our study, respectively. Intraclass correlation coefficient (ICC) estimate and its 95% confident intervals was calculated using SPSS package (IBM SPSS statistics 22) based on the absolute-agreement, 2-way random-effects model. The ICC of two raters was 0.967 (CI: 0.801–0.995, α = 0.05) which was considered as significant. Results have been illustrated in Table 2 for pretreatment, posttreatment, and follow-up phases.

Table 2

Results for sentence intelligibility in comparison with the original study.

		Pre *M*(*SD*)	Post *M*(*SD*)	FU *M*(*SD*)
% Sentence Intelligibility	This Study	53.53	91.82	**78.19**
	Original Study	86.55(16.39)	94.91(7.31)	**93.54(11.03)**

Note. Pre: pretreatment; Post: posttreatment 1; FU: follow-up.

Results of DDR and MPT for pretreatment, posttreatment, and 4 months after treatment are summarized in Table 3. The only measures which increased with the intervention and remain better than initial assessment were /ke/ and MPT that improved by 1 s.

The percentage of repeated in whole words decreased by 16.17% in posttreatment assessment, yet it increased by 11.42% after 4 months (see Table 4). This has however remained more than 4% better than the initial assessment.

Table 3

Comparative outcomes for diadochokinetic rate and maximum phonation time.

		Pre	Post	FU
Diado	/pe/	3.6	3.6	**2.53**
	te//	2.2	1.9	**1.70**
	/ke/	1.2	1.9	**2.35**
	/pe, te, ke/	1.2	1.7	**1.40**
MPT		14.3	15.61	**15.36**

Note. Pre: pretreatment; Post: posttreatment; FU: follow-up; MPT: maximum phonation time.

Table 4

Mean of speech rate and percentage of repeated words.

	Pre	Post	FU
WPM	75.78	60.78	**57.00**
PRW %	25.58	9.41	**20.83**

Note. WPM: words per minute; PRW: percentage of repeated words.

Everyday Communication Outcomes

The psychological impact of dysarthria from the perspective of speaker was investigated with Dysarthria Impact Profile (DIP), a questionnaire in five sections, over three assessments phases within the Be Clear program (Walshe, Peach, & Miller, 2009). DIP evaluates the impacts of dysarthria on the affective and communicative aspects. Since the questionnaire had not been translated into Persian, the participant was asked to describe his communicative alterations. He wrote:

> Previously, almost no one could understand my words, but I trust I'm doing much better now. My memory has picked up. In addition, my relationship with friends has notably improved. I could recently go for field visits to evaluate two mines as a part of my job responsibilities and could more confidently provide a verbal report in our meetings. I am going to the office once or twice a week. I am kind of confident to get rehired.

Since this study focused solely on speech skills, the participant's cognitive profile was not thoroughly measured; meanwhile, his subjective as well as family reports appeared to indicate a notable progress.

qEEG Measures

Resting-state 19-channel EEG data suggested a focal transient slowing at P3, P4, T8, T6, and C2 derivations favoring nonspecific brain dysfunction. Spectral topography suggested an increased alpha amplitude in posterior brain regions.

The NRsign software was used to analyze the real-time data with respect to spectral and spatial distribution of the brain waves including α (alpha), β (beta), θ (theta) frequency, and β2 as the user defined range (15–18 Hz).

Accordingly, the task-concurrent data analyses revealed an event-related desynchronization (ERD) at T4 and T3 with episodic slowing at T5, T6, P3, and P4. The ERD was also seen in FP2, F4, and F3 upon task-concurrent EEG. Based on the analysis, the bihemispheric frontal polar areas and frontotemporal β2 (15–18 Hz) were planned to gain through tES neuromodulation.

General assessment of the EEG signals showed no abnormality in terms of focal or paroxysmal EEG signals including sharp waves or spikes across brain regions.

The amplitude of distributed signals was mapped on a multiwindow color-coded (heat) maps showing an increased amplitude for θ frequency in bilateral centrotemporal area as well as bioccipital brain regions. In the right centrotemporal, β power was increased when the patient was reassessed following interventions, after 10 sessions as outlined in Figure 2-C. The subsequent qEEG-based evaluation demonstrated an improved spectral and spatial distributions in brain waves showing that θ and α distributions were more pronounced in specific brain regions predominantly involved in speech. There was also an apparent α–θ coherence in the left posterior brain regions as well as centrotemporal areas. The spectral up-band was set at 6 μV across frequency bands.

Discussion

In this study, we investigated the feasibility of an intensive treatment, adopted from the Be Clear program combined with tDCS-based neuromodulation, to improve speech intelligibility in a patient with dysarthria following TBI.

Our patient demonstrated remarkable improvement following intervention in terms of perceptual ratings of speech intelligibility which sustained upon a 4-month follow-up. Based on our findings, we could attribute the superiority in outcome to the application of tDCS in speech and language disorders (Baker, Rorden, & Fridriksson, 2010; Marangolo, 2013; Monti et al., 2013). This might even be applicable for the improvement of language skills in healthy individuals (Sparing, Dafotakis, Meister, Thirugnanasambandam, & Fink, 2008).

The striking issue with our participant was very low speech intelligibility at the prime of the process (53.53%). However, this measure reached up to over 90% after the intervention. One of the negative findings in our investigation was an approximately 13% decrease in this measure after 4 months. Meanwhile, the intelligibility was still above 24% higher than the initial score. This can be at least partly justified by the short duration of the intervention.

Although the main study reported that the effect of intervention on improving communication attitudes was not significant, the participant in the present study presented a very positive report of his communicative progress. This can be attributed to very low initial intelligibility. Of course, we believe that the role of tDCS application should not be ignored. According to his report, it appears that such an improvement has partly been due to increased levels of the patient's conscious competence. This finding is consistent with studies investigated the effect of tDCS on the level of self-awareness in healthy individuals (Lauro et al., 2014) and patients with abnormal levels of consciousness (Bai et al., 2017; Zhang et al., 2017). The reduction in speech rate and decreased palilalia were other endpoints of this study. Although initial speech rate was lower than normal (about 75 words per minute), explosive pattern with fast words and phrases repetition following prolonged pauses due to spastic dysarthria and blocks in vowel and back consonants resulted in very low ineligibility along with an unusual pattern of speech. Memory and vigilance problems were thought to be contributing to these pauses. One of our clinical objectives was to reduce the speech rate to increase the patient's control over the acoustic speech signals using the KR feedback. The result of this intervention reflected in the reduction of repetitive words percentage in our posttreatment evaluation.

Despite the fact that the obtained clinical response in the reduction of speech rate remained sustainable, there has been an increase in the number of repetitions in the follow-up phase. Given the subcortical origins for palilalia, it seems that nonspecific, hypoxic brain damage in the present case has led to this predicament. Although tDCS and tACS have the potential to influence the abnormal cortical-subcortical networks which are involved in Parkinson's Disease (Hess, 2013), we suspect that the low efficiency of subcortical effects of tDCS resulted in an insufficient impact in the present case.

On the other hand, it seems that the application of KP feedback (easy onset) and KR feedback (attention to explosive nature of speech signal) resulted in an increased DDR of /ke/ in posttreatment and follow-up phases. Meanwhile, reduction of DDR of /pe/ and /te/ was contrary to our expectations. A plausible justification is that he tried to increase the clarity with a slowing down the rate of speech.

In line with speech and vigilance alteration there were improvements in qEEG results. According to Gehrig, Wibral, Arnold, and Kell (2012), speech production tasks are expected to decrease α power primarily in visual and auditory cortices. A decrease in inhibitory α could engage these brain regions in the reading/speech production network; hence, α decrease is markedly lateralized to the left and over the secondary auditory cortices (Gehrig et al., 2012). Moreover, the increased amplitude for θ frequency in bilateral centrotemporal areas as well as bioccipital brain regions which was found to be predominant in the left hemisphere in posttreatment and follows-up phases turned out to be consistent with our findings. On the other hand, though Giraud et al., believe that slow fluctuations in 3–6 Hz EEG rhythms most strongly correlate with the spontaneous neural activity over the right auditory region, higher-frequency fluctuations in the 28–40 Hz range shows left hemispheric predominance (Giraud et al., 2007). That said, we observed almost the opposite (i.e., an increased beta power over the right centrotemporal regions after the intervention).

The overall portrayal of the present case of TBI-related chronic dysarthria shows a significant improvement in speech intelligibility (the most important symptom measured in dysarthria) after 2 weeks of intervention. This outcome, although at a single-case study level of evidence, may open new avenues to study such a tDCS-included protocol to ameliorate dysarthria symptoms following TBI in future sham-controlled clinical trials.

Conclusion

According to the present case's preliminary assessment and postintervention evaluation for speech function, we conclude that, although at a case-study level, tDCS may retain the potential in remediating speech insufficiencies, mainly intelligibility, in cases with TBI. Meanwhile, further research would be required to shed more lights on mechanistic peculiarities of such an approach in ameliorating speech predicaments following TBI. Further investigations to compare traditional speech therapy with sham- vs. true-tDCS would be warranted to explain the significance of such an approach in clinical settings.

Author Disclosure

Authors have no grants, financial interests, or conflicts to disclose.

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Evaluating the Effects of Online tDCS with Emotional *n*-back Training on Working Memory and Associated Cognitive Abilities

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Abstract

Working memory (WM) is a core cognitive ability important for everyday functioning. A burgeoning area of research suggests that WM can be improved via working memory training (WMT) paradigms. Additionally, recent research has shown that WM may be enhanced through noninvasive neuromodulation such as transcranial direct current stimulation (tDCS). In this study, we evaluated how a single-session, brief-but-concentrated combination of tDCS over the left dorsolateral prefrontal cortex (dlPFC; F3 region), paired with a WMT paradigm utilizing emotional stimuli (emotional *n*-back) could produce gains in WM and associated, untrained cognitive abilities. Healthy undergraduate participants were randomized to receive either active tDCS and WMT, or sham-tDCS and WMT. Cognitive abilities (WM, attention control, and cognitive inhibition) were measured before and after the intervention. No significant differences were found in WM performance or associated abilities between those who received active or sham tDCS. Individuals in both groups evidenced a faster reaction time on an Operation Span task, and an Emotional Stroop Task, following the WMT session. These findings add to the mixed picture of the effectiveness of single-session WMT protocols and highlight the importance of the dose-response relationship in training core cognitive processes such as WM.

Keywords: tDCS; working memory training; *n*-back; dlPFC

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Introduction

Working memory (WM) is a cognitive ability with a limited capacity related to temporary storage and manipulation of information (Baddeley, 1992). WM is critically important when executing multiple tasks and informing behavior choices for upcoming events (D’Esposito & Postle, 2015). Deficits in WM function have been linked to failure in real-world tasks (Beilock & Carr, 2005) and in potentiating emotional problems such as depression and anxiety symptoms (Matsuo et al., 2007; Moran, 2016).

Recent research has suggested that WM is a malleable cognitive process that can be improved with focused training. Meta-analyses suggest that WM training (WMT) programs such as the *n*-back task can positively affect WM processes that have been directly trained (Melby-Lervåg & Hulme, 2013), and others have suggested that WMT can produce transfer gains on general fluid intelligence (Jaeggi, Buschkuehl, Jonides, & Perrig, 2008). WMT is generally administered over multiple sessions in short (20-min) intervals (Soveri, Antfolk, Karlsson, Salo, & Laine, 2017). Moreover, positive training effects from WMT can be enhanced by using emotionally relevant stimuli (Hur, Iordan, Dolcos, & Berenbaum, 2017). For instance, *n*-back training with emotional stimuli has been shown to produce changes in psychiatric symptoms such as posttraumatic stress disorder (Larsen et al., 2019; Owens, Koster, & Derakshan, 2013; Sari, Koster, Pourtois, & Derakshan, 2016; Schweizer et al., 2017). Additionally, emotional WMT paradigms have been shown to increase the efficiency of the frontoparietal cognitive control network that is critical for WM function (Schweizer, Grahn, Hampshire, Mobbs, & Dalgleish, 2013; Schweizer, Hampshire, & Dalgleish, 2011).

A promising means to further enhance WMT is to utilize a direct brain stimulation approach such as transcranial direct current stimulation (tDCS). tDCS is a noninvasive form of brain stimulation purported to alter cortical excitability (Nitsche et al., 2003). Meta-analyses suggest that tDCS can significantly enhance WM capabilities and reaction time on cognitive tasks when paired with WMT (Brunoni & Vanderhasselt, 2014; Mancuso, Ilieva, Hamilton, & Farah, 2016). Considerable evidence suggests that key components of WM function are housed in the frontal lobe structures of the brain, particularly within the dorsolateral prefrontal cortex (dlPFC; Barbey, Koenigs, & Grafman, 2013; Eriksson, Vogel, Lansner, Bergström, & Nyberg, 2015). As such, many studies utilizing tDCS to alter cortical excitability related to WM target the dlPFC (Plewnia, Schroeder, Kunze, Faehling, & Wolkenstein, 2015; Ruf, Fallgatter, & Plewnia, 2017; Schulze, Grove, Tamm, Renneberg, & Roepke, 2019). Considering the ease of use and safety of the device (Bikson et al., 2016), tDCS and stimulation of the dlPFC has potential to augment the power of existing WMT programs.

Significant questions remain regarding the facilitative effect of tDCS on WMT, however. Firstly, there is mixed evidence regarding the necessary training threshold of pairing tDCS and WMT to produce cognitive gains. Some have suggested that a single session of tDCS can produce neurocognitive gains in WM (Fregni et al., 2005). However, others have suggested that tDCS, with or without WMT, needs repeated administration to induce long-term potentiation (Alonzo, Brassil, Taylor, Martin, & Loo, 2012; Meinzer et al., 2014), yet others have suggested that tDCS has little effect on cognitive function at all (Horvath, Forte, & Carter, 2015). Within the literature, the strength and duration of current delivery is also varied, but generally kept within 1 milliampere (mA) administered for approximately 5 to 30 minutes with few studies providing stimulation on the upper end of this duration (Clarke, Browning, Hammond, Notebaert, & MacLeod, 2014; Filmer, Lyons, Mattingley, & Dux, 2017; Nitsche et al., 2003; Ruf et al., 2017). If a brief but concentrated tDCS-WMT training paradigm can produce changes in core cognitive capabilities, such an intervention can be easily transported and utilized in a variety of contexts where WM is impacted. Thus, if a single-session training with a concentrated electrical and cognitive dosage could produce a therapeutic signal, there would be grounds for further exploration of such an intervention.

Secondly, while most *n*-back training paradigms use nonemotional stimuli to train WM processes (Soveri et al., 2017), such WM processes are intricately tied to underlying emotional valence. For instance, memory processes for emotional stimuli may be enhanced due to connections between the amygdala and cortical regions (Dolcos, LaBar, & Cabeza, 2004), and conversely diminished during aggravation of negative affective and anxiety states (Figueira et al., 2017; Moon & Jeong, 2015). Recent work suggests that WMT programs can be enhanced by training WM processes using emotional stimuli (Larsen et al., 2019; Schweizer et al., 2013). Despite the potent link between WM and emotional content, very few studies utilize emotional WMT in conjunction with tDCS (Martin et al., 2018; Schmidt, Wolkenstein, & Plewnia, 2015). Additional research is needed to explore how the combination of tDCS and emotional WMT can enhance cognitive training outcomes.

In this study, we sought to explore the usefulness of a single, concentrated, cognitive training paradigm in improving WM and associated cognitive abilities. To this end, we sought to amplify the tDCS-WMT paradigms used in previous studies by incorporating emotional valence in our cognitive training task and increasing the dosage of both WMT and tDCS in terms of time in the context of a single session. We hypothesized that individuals receiving anodal direct current stimulation in conjunction with emotionally valanced WMT would show improvements in both WM performance and transfer improvements in untrained but closely associated cognitive abilities such as attention control and cognitive inhibition.

Method

Participants

Forty-four (*n* = 44) undergraduate students between ages 18 and 60 were recruited from a university in the Midwestern United States. This study utilized a nonclinical student sample (healthy individuals) who were free of active psychiatric complaints, were not prescribed psychotropic medications, and did not report a history of head injuries or neurological complaints (e.g., history of seizures). A healthy sample was recruited for this study to factor out the deleterious effect of psychiatric comorbidities on WM processes (Lukasik, Waris, Soveri, Lehtonen, & Laine, 2019; Salazar-Villanea, Liebmann, Garnier-Villarreal, Montenegro-Montenegro, & Johnson, 2015).

Of the 264 participants who completed the prescreening, 86 individuals passed the prescreening criteria and were invited to participate in a full eligibility (FE) assessment. Fifty-seven individuals consented to participation, and 47 of those met study entry criteria; 10 individuals were excluded for reasons such as metal implants, history of concussions, or active psychotropic medications. Forty-seven participants completed the FE, but three individuals withdrew participation prior to randomization. Full demographic and clinical information of our sample is found in Table 1. The experimental and placebo groups did not significantly differ from each other regarding gender or age, or in baseline characteristics such as cognitive performance, or baseline anxiety.

Table 1
Demographic and clinical characteristics of the study sample

	tWMT *M*(*SD*) (*n* = 22)	sWMT *M*(*SD*) (*n* = 22)	*t*	*χ*2	*p*
Age	28.73(12.50)	27.54(11.23)	0.33		0.74
Gender (% Female)	72.7% (*n* = 16)	68.2% (*n* = 15)		0.13	0.94
Race					
White	63.6% (*n* = 14)	68.2% (*n* = 15)			
African American	13.6% (*n* = 3)	9.1% (*n* = 2)			
Asian	9.1% (*n* = 2)	9.1% (*n* = 2)			
Other	13.6% (*n* = 3)	9.1% (*n* = 2)			
Ethnicity (Hispanic or Latino)	0% (*n* = 0)	4.5% (*n* = 1)			
DASS-21					
Total	5.82(5.49)	5.91(7.89)	−0.04		0.97
Depression	1.91(2.99)	1.45(2.91)	−0.51		0.61
Anxiety	1.64(2.60)	1.55(2.04)	0.13		0.90
Stress	2.82(3.42)	2.36(2.59)	0.50		0.62

Note. tWMT = working memory training plus active direct current stimulation; sWMT = working memory training plus sham direct current stimulation; DASS-21 = depression, anxiety, and stress scale.
*p < .05; **p < .01

Study Procedures

A study flow-chart is found in Figure 1. Interested participants were invited to complete a prescreening survey including an online prescreening consent form, Diagnostic History Scale (DHS; a researcher-made 14-item self-report measure to assess the presence of any comorbid psychiatric conditions or allergies that may affect study participation), and Safety Screening Questionnaire (SSQ; a 17-item self-report measure that asks about contraindications to tDCS stimulation). Those who did not report current psychiatric complaints, alcohol and substance use, history of concussions or head injuries, mental implants in head, history of seizure, epileptiform, or migraines, and concomitant psychotropic medications were invited to the FE session. Written informed consent was obtained in person at the laboratory visit prior to any study activities. All study procedures were approved by the university's Institutional Review Board (IRB).

The remainder of study procedures took place over a single session. Participants were first reassessed for eligibility criteria using the Mini International Neuropsychiatric Interview (MINI) version 6.0, DHS, and SSQ (semi-structured interview format) to ensure safety for participation.

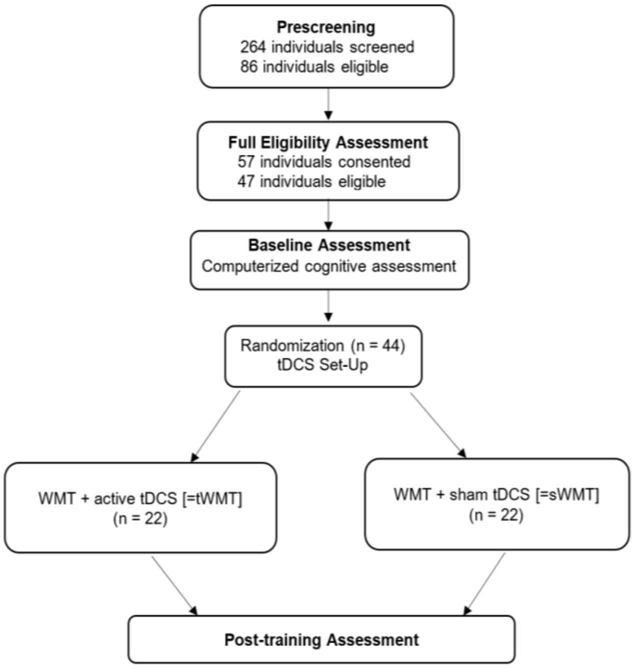

Figure 1. Flow of study procedures.

Following verification of study eligibility, participants were assessed using a battery of computerized cognitive tests to measure WM and attention. Cognitive function was measured at baseline (BL), and again following training (posttraining [PT]). The Depression Anxiety and Stress Scale (DASS-21) was used to measure depression, anxiety, stress, and general negative affect at BL (Lovibond & Lovibond, 1995). While we targeted a healthy sample to factor out the effect of psychiatric comorbidity on cognitive function, we measured the general level of emotional symptomology in our sample to further identify any confounding effects of negative affect on cognitive function. Computerized cognitive assessment and training paradigms were presented using E-Prime 2.0 (Psychology Software Tools, Inc., Sharpsburg, PA), and the remainder of computerized assessment used Inquisit software (Millisecond Software, Seattle, WA). Questionnaires were administered using Qualtrics Survey Tools (Qualtrics, Provo, UT).

Randomization took place after BL assessment according to the following schedule: either WMT + active tDCS group (tWMT; *n* = 22), or WMT + sham tDCS group (sWMT; *n* = 22). Following randomization, the tDCS apparatus was attached, and participants completed 60 min of WMT. This training period was approximately two to three times the regular dose of one WMT session typically used in the literature (Larsen et al., 2019; Schweizer et al., 2013). Participants in the tWMT condition received 30 min of current stimulation while training WM processes, and participants in the sWMT only received 30 s of stimulation (ramp-up) to induce the feeling of stimulation (i.e., tingling). Stimulation started immediately upon trial 1 of the *n*-back paradigm. Thus, tWMT received online direct current for half of their training session, while sWMT participants essentially completed a 60-min memory training session without stimulation. Following WMT, participants repeated computerized cognitive assessment from BL to measure a pre-to-post change in memory and associated cognitive abilities.

Computerized Cognitive Assessment

Working memory (automated complex span tasks [ACST]). WM performance was the primary outcome measure in this study. WM was measured through the automated complex span tasks (ACST; Oswald, McAbee, Redick, & Hambrick, 2015), which was comprised of three computerized span tasks to measure discrete aspects of WM processing. The operation span task prompted participants to solve a series of math operations while remembering a set of unrelated distractor numbers. The reading span task presented participants with sensical and nonsensical sentences (approximately 10–15 words long) and asked participants to differentiate which they were while also remembering the order of a string of digits. In the symmetry span task, participants were presented with a set of 8x8 matrices of black and white squares, and participants were instructed to judge whether the matrices were symmetrical or asymmetrical along a vertical line while also remembering the location of a red square positioned in a 4x4 matrix. Each span task provided two indices of WM function: *absolute scores* referred to the number of trials in which a participant recalled all target stimuli in order without error and *relative scores* referred to the proportion of correct responses.

WM training paradigms have also been shown to induce transfer effects on untrained cognitive tasks (Jaeggi et al., 2010), and WM has been shown to be critically important for overall allocation of attentional resources, especially in threat contexts (Stout, Shackman, Johnson, & Larson, 2015; Stout, Shackman, & Larson, 2013). Thus, we used the following tasks as secondary outcome measures to probe transfer effects of our training protocol:

Interference control (emotional Stroop task [EST]). The EST presented words from three distinct categories (neutral, positive, and negative) and prompted participants to select, with colored keys on the keyboard, the color of the word on the computer screen. The EST is useful in identifying interference effects in processing emotional stimuli, such that longer reaction times (RT) indicate greater difficulty in processing information effectively. The EST produced a general RT index for each word condition (e.g., Negative RT, Neutral RT, etc.), and a bias score for each word category by subtracting the neutral RT from the category RT (e.g., Negative Bias = Negative RT – Neutral RT). Participants were tested with one practice block (20 trials) and one test block (75 trials; Smith & Waterman, 2003).

Attentional control (attention network task [ANT]). We utilized the brief ANT to measure overall efficiency in attentional networks. Participants were presented with a fixation cross (400 ms), followed by five directional arrows arranged in a line. Participants responded quickly to identify the direction of the central arrow (left or right). The arrows flanking the central target either provided congruent information (e.g., all arrows were pointing in the same direction), or incongruent information (e.g., arrows flanked the central target with random left/right directions). Participants were tested with one practice block (12 trials), and three test blocks (48 trials each). The ANT provided three indices of attentional control: (1) alerting (achieving and maintaining alertness); (2) orienting (orienting attention to a specific location); and (3) conflict (resolving conflict between incongruent stimuli; Fan, McCandliss, Sommer, Raz, & Posner, 2002).

Computerized Working Memory Training

WM was trained with an emotionally adaptive dual *n*-back task. This WMT involved a presentation of emotionally salient faces and words to target constant updating of information in WM and shifting between two different modes of stimuli (Larsen et al., 2019). In each trial, one of eight fearful faces (4 males and 4 females) was presented within a 3×3 grid while a negative spoken word (female voice; disaster, cancer, etc.) was simultaneously delivered. The *n* refers to how many trials back from the current trial a participant must withhold in their working memory. Thus, to achieve a correct response, participants had to determine whether the location of a face and word stimuli presented in the current trial matched the face location and word presented *n*-trials back (e.g., 1-trial back, 2-trials back, etc.). The task is both a cognitive training tool and assessment modality in that practice on the task is thought to empower working memory abilities, and data from each session provides an index of working memory performance at that point in time. The task was adaptive, and training began at the 1-back level and progressed depending on performance through the entirety of the hour training session. Difficulty was raised (i.e., 2-back, 3-back, 4-back) contingent on performance accuracy over 95% for both modalities (i.e., faces and words). A performance accuracy of less than 75% lowered the difficulty level by 1-back. The last level of *n*-back was carried across blocks so that performance was continuous. Though the task was adaptive, the *n*-back would not be classified as neurofeedback because participants were not encouraged to modify performance based on physiological readings. Training took place over four blocks (first block = 30 min, blocks 2–4 = 10 min each).

tDCS placement and dosage. Following BL assessment and randomization, participants were offered a short break before attaching the tDCS apparatus. Electrode sponges were moistened with 0.9% saline solution and wrung out to release excess liquid. Participants were seated in front of the computer monitor, and the target area for stimulation (left forehead) was wiped with an alcohol wipe. Placement of the anodal (positive) electrode was over the F3 region to stimulate the dlPFC (Hill, Fitzgerald, & Hoy, 2016). Electrodes were placed according to the 10–20 international positioning system using the positioning tool reported by Beam, Borckardt, Reeves, and George (2009). We utilized 2x2 Amrex electrodes. The stimulator used was the Chattanooga Ionto dual channel electrophoresis system (DJO LLC [Chattanooga Rehab], Dallas, TX), which has been used in previous research exploring the effect of tDCS on emotional processing (Clarke et al., 2014). The cathodal (negative) electrode was placed on the left superior region of the trapezius muscle near the base of the participant's neck so that no stimulation was given to other brain regions. This reference electrode was kept in place by a rubber strap over the participants' shoulder.

tDCS stimulation for the active condition (tWMT) was fixed at 1.0 mA for 30 min of stimulation. Thus, charge density (mA/cm^2) was fixed at 0.0387mA/cm^2 in line with safety criteria for stimulation (Bikson et al., 2016; Nitsche et al., 2003). Stimulation began when participants initiated their first practice block and continued for 30 min. Ramp-up time was approximately 30 seconds. Study staff was present for the duration of the stimulation and probed for discomfort or adverse events after each training block. For sham stimulation (sWMT), setup occurred the same way, but the stimulator was only turned on for the ramp-up portion (approximately 30 seconds) to induce a feeling of stimulation, and then turned off. Participants in the sham condition also received discomfort and safety monitoring between training blocks.

Results

Demographic and Baseline Variables

There were no significant group differences in terms of age or gender. No between group differences were observed on various measures at pretraining, including the ACS or DASS-21 (Table 1).

Data Cleaning

Response times for all cognitive tests were taken across individual participant's mean latencies for correct responses. Any trials that exceeded the participant's average response time by 2.5 standard deviations were deleted. Based on this data cleaning procedure, approximately 2.86% of trials were removed per person on average.

Working Memory Performance During Training (*n*-back Task)

The average *n* from the *n*-back task was calculated for each participant across all four blocks. Results are shown in Table 2. An independent samples *t*-test revealed no working memory differences in the average *n* between groups. The average highest *n* obtained across four blocks was 2.70 (*SD* = 0.50) and 2.80 (*SD* = 0.36) for tWMT and sWMT, respectively. The average *n* obtained across four blocks for the tWMT condition was 1.92 (*SD* = 0.39), and sWMT was 2.08 (*SD* = 0.31).

Table 2

Average n achieved on the n-back working memory training task

	tWMT *M*(*SD*)	sWMT *M*(*SD*)	*t*	*p*
Block 1	1.64(0.30)	1.80(0.40)	1.44	0.16
Block 2	2.04(0.50)	2.15(0.33)	0.86	0.40
Block 3	2.00(0.46)	2.16(0.36)	1.36	0.18
Block 4	2.00(0.46)	2.20(0.37)	1.53	0.14

Note. tWMT = working memory training plus active direct current stimulation; sWMT = working memory training plus sham direct current stimulation. **p* < .05; ***p* < .01

Working Memory Performance after Training

We hypothesized that those in the tWMT group would improve WM performance on tasks of mathematical operations, reading, and symmetry relative to those in the sWMT group. A 2 (condition) x 2 (time) repeated measures analysis of variance (ANOVA) was conducted to compare between group changes pre- and posttraining. The span tasks were analyzed using absolute and relative values as described in the methods section. These data are presented in Table 3.

The Operation Span task yielded significant positive main effects of time for absolute and relative scores, but no group by time interactions were found for either absolute or relative scores. The Reading Span task yielded no significant main effects of time for absolute or relative scores, or group by time interactions for absolute or relative scores. The Symmetry Span task yielded no significant main effects of time for absolute or relative scores, or group by time interactions for absolute or relative scores.

Cognitive Inhibition and Attentional Control

We predicted that those who received tWMT versus sWMT would improve related, untrained cognitive abilities in cognitive inhibition and attentional control. A 2 (condition) x 2 (time) repeated measures ANOVA was conducted for the following cognitive measures.

Emotional Stroop. The EST was evaluated through two indices: (1) overall RT and (2) Stroop interference effects (bias). Results are shown in Table 4. There was a main effect of time, such that RT became shorter (i.e., faster reaction time) for neutral words, positive words, and negative words. No significant differences were observed for group x time interaction for differences in RT between groups on neutral words, positive words, or negative words. Finally, in terms of interference effects, no significant main effects of time were observed between groups for negative words or positive words. Further, no significant group x time interaction effects were observed between group

Table 3

Working memory performance before and after the computerized training program

		tWMT *M*(*SD*)	sWMT *M*(*SD*)	ME Time	*d*	95% CI	Time x Group	*d*	95% CI
Operation Span									
Absolute	Pre	13.48(8.52)	14.91(7.97)	*F*(1,41) = 11.71, *p* < .01**	1.06	[0.42, 1.70]	*F*(1,41) = 0.57, *p* = .46	0.20	[−0.40, 0.80]
	Post	16.38(7.42)	19.45(8.90)						
Relative	Pre	21.05(5.90)	21.86(5.61)	*F*(1,41) = 4.76, *p* = .03*	0.67	[0.06, 1.28]	*F*(1,41) = 0.34, *p* = .56	0.20	[−0.40, 0.80]
	Post	22.33(6.92)	24.09(7.43)						
Reading Span									
Absolute	Pre	9.48(7.93)	12.23(8.29)	*F*(1,41) = 1.32, *p* = .26	0.35	[−0.25, 0.95]	F(1,41) = 0.35, p = .56	0.20	[−0.40, 0.80]
	Post	12.29(9.60)	13.14(7.55)						
Relative	Pre	18.38(6.45)	21.55(5.84)	*F*(1,41) = 0.25, p = .62	0.16	[−0.43, 0.76]	F(1,41) = 0.04, p = .84	0.006	[−0.59, 0.60]
	Post	19.14(8.46)	21.86(6.20)						
Symmetry Span									
Absolute	Pre	7.52(6.13)	8.24(6.05)	*F*(1,40) = 0.11, p = .74	0.11	[−0.50, 0.72]	F(1,40) = 0.01, p = .92	0.06	[−0.55, 0.67]
	Post	7.95(4.64)	8.48(5.14)						
Relative	Pre	13.90(5.99)	14.43(5.21)	*F*(1,40) = 1.11, p = .30	0.35	[−0.26, 0.96]	F(1,40) = 0.04, p = 0.83	0.06	[−0.55, 0.67]
	Post	14.90(3.62)	15.10(5.42)						

Note. 95% confidence intervals (CI) were calculated for associated effect size estimates (*d*). tWMT = working memory training plus active direct current stimulation; sWMT = working memory training plus sham direct current stimulation. **p* < .05; ***p* < .01.

for negative words or positive words. Overall, while main effects of time were observed for overall RT from pre- to posttraining, no other main effect or group x time interaction differences were observed between groups.

Attention network task (ANT). The ANT was evaluated across three indices: alerting, orienting, and conflict. Results are found in Table 5. No significant main effects of time were found for alerting, orienting, or conflict. There were also no significant group x time interactions for alerting, orienting, or conflict. Overall, no significant main effects of time or group x time interactions were observed for the ANT between groups.

Conclusion

WM is highly important in everyday cognitive functioning and has been proposed to be malleable through focused cognitive training programs (Jaeggi et al., 2008; Melby-Lervåg & Hulme, 2013). tDCS has been proposed as a noninvasive means of increasing brain activation, which may in turn result in significant improvements in WM when paired with such training programs (Brunoni & Vanderhasselt, 2014; Mancuso et al., 2016). Further, the use of emotional stimuli in WMT has been demonstrated to result in beneficial alterations in affect regulation as well as corresponding neural circuitry (Larsen et al., 2019; Schweizer et al., 2013, 2011). To this end, the present study sought to examine how a single session of tDCS-WMT, amplified with emotional valence, and dosage of training and electrical current, might improve WM capabilities and produce transfer effects on associated untrained cognitive processes. Performance across a range of WM domains was compared before and after WMT paired with active tDCS, versus sham tDCS. Contrary to study hypotheses, no group differences were found in the primary outcomes of working memory, and no group differences were found in untrained transfer abilities.

We did find that individuals in both training conditions evidenced faster reaction times on both the operation span task and the emotional Stroop task following the WMT session. The magnitude of these effects ranged from small to large and the direction of these effects suggested that individuals showed better cognitive performance over the course of the study overall. Considering that faster RT was observed in both groups, this change may

Table 4

Interference control performance (Emotional Stroop Task) pre- and posttraining

		tWMT *M*(*SD*)	sWMT *M*(*SD*)	ME Time	*d*	95% CI	Time x Group	*d*	95% CI
Overall RT									
Neutral	Pre	683.05(105.44)	678.77(109.38)	*F*(1,42) = 20.82, *p* < .01**	1.40	[0.74, 2.06]	*F*(1,42) = 2.98, *p* = .09	0.55	[−0.05, 1.15]
	Post	644.49(101.58)	593.24(60.91)						
Positive	Pre	675.81(97.90)	658.43(96.86)	*F*(1,42) = 26.84, *p* < .01**	1.60	[0.92, 2.29]	*F*(1,42) = 1.47, *p* = .23	0.35	[−0.25, 0.95]
	Post	627.39(91.56)	580.40(73.66)						
Negative	Pre	676.25(90.20)	660.55(67.42)	*F*(1,42) = 37.31, *p* < .01**	1.88	[1.17, 2.59]	*F*(1,42) = 1.53, *p* = .22	0.41	[−0.19, 1.01]
	Post	637.77(66.65)	602.54(75.62)						
Bias									
Positive	Pre	−7.24(46.07)	−20.34(61.44)	*F*(1,42) = 0.01, *p* = .914	0.06	[−0.53, 0.65]	*F*(1,42) = 0.64, *p* = .43	0.20	[−0.39, 0.79]
	Post	−17.10(45.72)	−12.83(49.27)						
Negative	Pre	−6.80(62.44)	−18.22(80.19)	*F*(1,42) = 0.90, *p* = .35	0.29	[−0.30, 0.88]	*F*(1,42) = 0.89, *p* = .35	0.29	[−0.30, 0.88]
	Post	−6.73(56.56)	9.30(62.09)						

Note. 95% confidence intervals (CI) were calculated for associated effect size estimates (*d*). tWMT = working memory training plus active direct current stimulation; sWMT = working memory training plus sham direct current stimulation; RT = reaction time. **p* < .05; ***p* < .01.

Table 5

Performance on attention control (Attention Network Tasks [ANT]) Pre- and Post-Training

		tWMT Mean (*SD*)	sWMT Mean (*SD*)	ME Time	*d*	95% CI	Time x Group	*d*	95% CI
Alerting	Pre	19.61(33.40)	24.61(31.93)	*F*(1,41) = 0.27, *p* = .61	0.17	[−0.43, 0.77]	*F*(1,41) = 0.00, *p* = .98	0.06	[−0.53, 0.65]
	Post	22.58(23.24)	27.25(24.30)						
Orienting	Pre	54.58(43.68)	33.36(29.98)	*F*(1,41) = 0.04, *p* = .84	0.06	[−0.53, 0.66]	*F*(1,41) = 2.09, *p* = .16	0.46	[−0.15, 1.07]
	Post	46.63(32.25)	43.97(19.49)						
Conflict	Pre	91.46(99.53)	115.38(58.91)	*F*(1,41) = 0.68, *p* = .41	0.26	[−0.34, 0.86]	*F*(1,41) = 0.81, *p* = .37	0.28	[−0.32, 0.88]
	Post	115.96(37.89)	114.32(46.65)						

Note. 95% confidence intervals (CI) were calculated for associated effect size estimates (*d*). tWMT = working memory training plus active direct current stimulation; sWMT = working memory training plus sham direct current stimulation. **p* < .05; ***p* < .01.

be attributable to repeated assessment in a short window. Alternatively, faster RT on the operation span task and emotional Stroop may signal a reflection of improvements in efficiency in underlying memory cognitive network networks resulting from WMT. Previous research has suggested that WMT can indeed induce changes to produce faster reaction times (Thompson, Waskom, & Gabrieli, 2016). Moreover, visuospatial working memory, which was a significant component in our *n*-back training, has been shown to be important in understanding variance in reaction time (Bo, Jennett, & Seidler, 2011). Future research may benefit from more fine-grained analyses to explore how working memory, WMT paradigms, and reaction time distributions are connected.

There are likely numerous contributing factors to explain the lack of group differences between individuals who received active and sham tDCS. First and foremost, a single session of WMT, despite efforts to augment the strength of the training with emotional valence and tDCS, may not hold enough power to elicit significant change in the evaluated cognitive domains. Recent research suggests that the facilitative effects of WMT may be locked behind a dose-response relationship (Jaeggi & Buschkuehl, 2014), and that transfer effects to untrained cognitive processes may be moderated by the duration of training (Schwaighofer, Fischer, & Bühner, 2015). Deficient WM training effects may have yielded little room for augmentation effects by the tDCS manipulation, contributing to the lack of group differences.

Similarly, it is possible that the neurocognitive changes that follow tDCS are also subject to a dose-response relationship. While some work has shown that a single session of tDCS can evoke change in cognitive performance in a pathological (e.g., depressed) sample, neurostimulation may function differently in the context of healthy controls (Gögler et al., 2017). Alonzo et al. (2012) found that daily tDCS was more effective in producing changes in cortical excitability than tDCS administered every other day. While it is also possible that we applied insufficient electrical current to induce changes to performance, previous research has suggested that stimulation in the range of 1.0 mA is optimal in WM protocols (Hoy et al., 2013).

It is also possible that we did not observe a significant effect of tDCS and WMT on working memory because of the lack of a follow-up visit. Indeed, some researchers have described so-called “sleeper effects” in which transfer effects of WMT for children and adolescents were only found months after training had been completed (Van der Molen, Van Luit, Van der Molen, Klugkist, & Jongmans, 2010). While some researchers have highlighted the need for follow-up assessments (Holmes, Gathercole, & Dunning, 2009), the present study involved a very short assessment time window; participants underwent pretraining testing, WMT and tDCS, and posttraining all in the span of a single lab visit which did not allow for any long-term delayed outcomes to be assessed. Individual differences such as preexisting cognitive abilities, motivation, enjoyment of cognitive challenges, beliefs about the malleability of intelligence have also been implicated for shorter-term WMT (Jaeggi, Buschkuehl, Shah, & Jonides, 2014). It is also possible that WMT may not be as effective when presented in such concentrated format. The spacing effect, first identified by Ebbinghaus (2013/1885), posits that learning is most effective when spaced apart rather than completed in a short period of time. When considering the spacing effect alongside tDCS, researchers have shown that stimulation was more potent when spaced out over several days as compared to consecutive daily administration (Au, Buschkuehl, Duncan, & Jaeggi, 2016). Transfer effects of tDCS to affective processes may also not be found when WMT is presented in such a short, concentrated session. Further still, extant work suggests that a single session of tDCS alone is not sufficient to produce noticeable cognitive gains (Horvath et al., 2015).

In light of the present study’s results, the question arises of whether WMT is truly effective, a question that other researchers continue to debate. Some recent meta-analyses suggest that WMT has a small positive transfer effect on broader cognitive capabilities (Au et al., 2016; Karbach & Verhaeghen, 2014). However, other researchers highlight some of the above considerations (e.g., discounting differences in baseline cognitive abilities, ignoring the use of active versus passive control groups) as problems in these meta-analyses, instead arguing there is a dearth of evidence in support of WMT (Melby-Lervåg & Hulme, 2016). Some researchers have also found evidence for a publication bias in reporting significant effects of single-session tDCS studies (Westwood & Romani, 2017). Rather than investigating whether or not WMT and tDCS themselves work, some argue that researchers should be more concerned with what parameters of training work best for which individuals, and how much improvement individuals make within WMT (Jaeggi, Buschkuehl, Jonides, & Shah, 2011). Above and beyond WMT alone, other studies augmenting training with tDCS have found multiple sessions result in sustained gains in WM and untrained associated domains (Ruf et al., 2017). Again, perhaps the present study’s single-session design limits the possibility of significant effects being found.

The findings of this study should be considered in light of its limitations, with those limitations shaping directions for future research. This study utilized a relatively small sample size (i.e., 22 participants per group), and it is possible that a larger sample size would have produced significant group differences. Granted, the estimated effect sizes for our variables were within their associated 95% confidence internals; thus, it is also likely that additional data points would not have significantly altered the significance of findings.

While tDCS has been suggested to produce cognitive performance gains in a single session (Fregni et al., 2005), these claims have been disputed by other researchers (Alonzo et al., 2012; Meinzer et al., 2014). Future studies should consider multiple sessions of emotionally-laden WMT paired with tDCS. Finally, while this study compared active tDCS to sham tDCS, both groups completed an emotional *n*-back task. While the choice to use an emotional task was intentional given that tDCS has been implicated in improvements in affective and cognitive control, future studies might benefit from the inclusion of a neutral *n*-back task to investigate any potential group differences.

Despite largely null findings, the present study is methodologically sound and contributes to the newly growing body of tDCS literature. While our single session high-potency tDCS administration paired with an emotional *n*-back task did not result in significant changes across groups, the limitations addressed above provide future directions to explore within this area of work. As researchers continue to investigate the potential utility of WMT as a means of bolstering a wide range of cognitive functions and associated affective processes, it is imperative to explore mechanisms underlying these changes. For instance, are the positive changes resulting from WMT due to the brain working harder, or more efficiently? How far do possible transfer effects reach, and for how long? While our single session of WMT and tDCS administration did not result in any noticeable improvements or transfer effects, this allows researchers to narrow in on the minimal intervention needed to find such effects.

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