REVIEW ARTICLE

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Enhancing Emotion Regulation: A Review of tDCS Effects

Duygu Düzenlemesinin Geliştirilmesi: tDCS Etkilerinin İncelenmesi

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Abstract

Transcranial direct current stimulation (tDCS) has demonstrated increasing promise as a method of modifying brain activity and cognitive function. The objective of this comprehensive review of the literature is to evaluate the impact of tDCS on explicit and implicit emotion regulation strategies. An extensive review of the literature, conducted using keywords "tDCS," "emotion regulation," "implicit emotion regulation," and "explicit emotion regulation" in Google Scholar, PubMed, Scopus, and Web of Science databases, identified studies meeting the inclusion and exclusion criteria. Twenty studies overall, encompassing both implicit-automatic and explicit-controlled emotion regulation strategies, were found after an extensive review of the literature. There has been a lot of research conducted on explicit emotion regulation, however not as much on implicit emotion regulation. The review revealed that tDCS administration has demonstrated promising effects on enhancing emotion regulation performance across various tasks and neural targets. Nevertheless, inconsistencies in the literature highlight the necessity for further research to elucidate the precise mechanisms underlying tDCS-induced changes in emotion regulation, as well as to explore individual differences in treatment response. In conclusion, this review highlights the potential of tDCS as a valuable intervention for enhancing emotion regulation processes, with implications for both clinical practice and basic research in affective neuroscience.

Keywords: Neuropsychology, tDCS, Explicit Emotion Regulation, Implicit Emotion Regulation.

Öz

Transkraniyal doğru akım stimülasyonu (tDCS), beyin aktivitesini ve bilişsel fonksiyonu değiştirme yöntemi olarak artan bir umut vaat etmektedir. Bu kapsamlı literatür taramasının amacı, tDCS'nin açık ve örtük duygu düzenleme stratejileri üzerindeki etkisini değerlendirmektir. Google Scholar, PubMed, Scopus ve Web of Science veritabanlarında "tDCS", "duygu düzenleme", "örtük duygu düzenleme" ve "açık duygu düzenleme" anahtar kelimeleri kullanılarak yapılan kapsamlı bir literatür taraması, dahil etme ve dışlama kriterlerini karşılayan çalışmaları belirlemiştir. Kapsamlı bir literatür taramasının ardından, hem örtük-otomatik hem de açık-kontrollü duygu düzenleme stratejilerini içeren toplamda yirmi çalışma bulunmuştur. Açık duygu düzenleme üzerine birçok araştırma yapılmış olmasına karşın, örtük duygu düzenleme üzerine o kadar fazla araştırma yapılmamıştır. İnceleme, tDCS uygulamasının çeşitli görevler ve nöral hedefler üzerinde duygu düzenleme performansını artırmada umut verici etkiler gösterdiğini ortaya koymuştur. Bununla birlikte, literatürdeki tutarsızlıklar, tDCS'nin duygu düzenlemedeki değişikliklere neden olan kesin mekanizmaları açıklığa kavuşturmak ve tedaviye yanıt veren bireysel farklılıkları araştırmak için daha fazla araştırmaya duyulan ihtiyacı vurgulamaktadır. Sonuç olarak, bu inceleme, tDCS'nin duygu düzenleme süreçlerini geliştirmede değerli bir müdahale olarak potansiyelini vurgulamakta olup, hem klinik uygulamalar hem de duygusal sinirbilim alanındaki temel araştırmalar için önemli etkileri bulunmaktadır.

Anahtar Kelimeler: Nöropsikoloji, tDCS, Örtük Duygu Düzenleme, Açık Duygu Düzenleme.

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Enhancing Emotion Regulation: A Review of tDCS Effects

Transcranial direct current stimulation (tDCS) is a non-invasive brain stimulation technique that uses subthreshold anode or cathode stimulation to modulate neural responses. This method affects mood or cognitive abilities by inducing long-term potentiation or short-term depression at the synaptic level. Therefore, tDCS has been utilized in the treatment of psychopathologies, such as mood disorders. Ongoing research is exploring the potential of tDCS in this area (Clarke et al., 2020).

Emotion regulation, which is relevant to both mood disorders and cognitive ability, has also been the subject of tDCS studies in order to maintain an individual's functionality, emotion regulation entails controlling the degree, frequency, and duration of emotional states (Chen et al., 2023). The literature identifies several kinds of emotion regulation (Braunstein et al., 2017). This in-depth review considers two types of emotion regulation strategies: explicit and implicit. Implicit emotion regulation is defined as a process that affects the character, strength, or duration of an emotional reaction without requiring deliberate involvement or stated goals. In contrast, explicit emotion regulation techniques entail a conscious endeavor to alter an individual's emotional state (Koole & Rothermund, 2011). Implicit emotion regulation strategies include extinction, reinforcer revaluation, and reversal learning. These strategies have been studied using the Emotional Stroop Task and the Go/No-Go Task. On the other hand, explicit emotion regulation strategies include reappraisal, selective attention, distraction and placebo.

The neuroscience of emotion regulation has been studied using functional neuroimaging methods (Sebastian & Ahmed, 2018). Studies focusing on brain lesions have emerged as a critical element in advancing our understanding of the neural mechanisms and cognitive aspects involved in emotion regulation (Turnbull & Salas, 2021). Research consistently indicates that while the prefrontal cortex and its associated areas are implicated in the regulatory processes of emotion, subcortical regions such as the amygdala are pivotal in the generation of emotions (Morawetz et al., 2020). From this perspective, emotion regulation is assumed to operate under the premise that the frontal brain regions exert control over the subcortical regions responsible for emotion generation (Min et al., 2022).

The aim of this systematic review is to assess whether experimental studies have shown enhanced emotion regulation abilities through the application of tDCS to neural networks associated with both explicit and implicit emotion regulation strategies. Earlier studies have identified a relationship between tDCS and a range of psychiatric disorders (Kekic et al., 2015). This review, however, focuses on the impact of tDCS on emotion regulation, aiming to provide a more comprehensive approach. Many psychiatric illness models emphasize the central role of emotion regulation, which is considered a core mechanism underlying various psychological disorders. The term "transdiagnostic" refers to processes or factors, like emotion regulation, that are not specific to a single diagnosis but instead influence a broad spectrum of psychological conditions. Emotion regulation, therefore, is widely recognized as a critical transdiagnostic factor contributing to the development and maintenance of multiple psychiatric disorders (Kraiss et al., 2020).

Theoretical Framework

tDCS as A Tool for Modulation Cognitive Function

Non-invasive brain stimulation (NIBS) techniques allow neuronal activity in the healthy human brain to be regulated both spatially and temporally (Bergmann & Hartwigsen, 2021). One non-invasive brain stimulation technique for subthreshold modification of neuronal activity and cognitive function is tDCS. An electrical stimulator that delivers a steady, isolating current coupled to two electrodes, an anode, and a cathode makes up the tDCS equipment. According to Kelley et al. (2019), these electrodes are applied to the scalp above the cortical areas of interest. Using scalp electrodes, tDCS applies a low, continuous electrical current (amplitude <2 mA) to alter brain activity. Following stimulation, its effects last for over an hour (Das et al., 2016). Despite its potential benefits, tDCS is associated with several common side effects, including mild skin irritation, tingling sensations, itching under the electrodes, and in some cases, transient headache or fatigue. These side effects are generally well-tolerated and diminish shortly after stimulation (Wysokiński, 2023).

The stimulation delivered in tDCS is subthreshold, meaning it is too weak to generate action potentials at the level of the transmembrane neuronal potential. Instead, it causes small changes that can either increase or decrease the likelihood of a neuronal response (Nejati et al., 2022). Anodal transcranial direct current stimulation has been demonstrated to improve neuronal excitability in the target brain region by depolarizing neurons, which makes them prone to produce action potentials. Increased neuronal excitability could enhance cognitive performance by increasing the efficacy of neural networks involved in working memory, inhibition, flexibility, and theory of mind (Concerto et al., 2017; Pisoni et al., 2018). Improvements in reaction times and accuracy across various cognitive tasks observed after anodal tDCS treatments lend support to the theory that enhancing neuronal excitability promotes faster and more accurate cognitive processing. Anodal tDCS achieves this by applying a positive electrical current to the targeted brain area, which depolarizes the neuronal membrane, lowering the threshold for action potential generation and increasing the likelihood of neuronal firing. This mechanism is thought to facilitate neural activity in underactive brain regions. On the other hand, cathodal tDCS applies a negative electrical current, leading to hyperpolarization of the neuronal membrane. This increases the action potential threshold, reducing neuronal excitability and dampening neural activity. This inhibitory effect is often utilized to suppress overactive circuits or rebalance abnormal brain activity patterns (Narmashiri & Akbari, 2023). According to Kelley et al. (2019), tDCS interacts with a variety of complex synaptic mechanisms, including long-term potentiation (LTP) and long-term depression (LTD), which are key processes underlying synaptic plasticity. LTP refers to a sustained increase in synaptic strength that occurs when neurons are frequently and strongly activated together, often described as the cellular basis of learning and memory. This mechanism enhances the efficiency of synaptic transmission, allowing for more robust communication between neurons (Pisoni et al., 2018). Conversely, LTD is a process that weakens synaptic strength over time, typically occurring when neuronal activity is less frequent or weaker. This reduction in synaptic efficacy is essential for neural network remodeling, enabling the brain to filter out less relevant information and maintain overall balance in synaptic activity (Edelmann et al., 2017; Ibrahim et al., 2021). Through these mechanisms, tDCS is believed to modulate neural plasticity and influence cognitive and behavioral outcomes (Cavaleiro et al., 2020; Vitureira et al., 2013). This approach influences cognitive functions and brain activity by enhancing hyper-communicative activity through the anode and reducing hypo-communicative activity through the cathode. The prolonged application of stimulation leads to sustained alteration of brain excitability and plasticity, which can manifest in one of two ways: potentiation or depression. This is dependent on the polarity of the stimulation. Nejati et al. (2022) observed that tDCS-induced changes in excitability and plasticity significantly modulate brain activity in various processes, affecting cognitive functions and brain processes. This interaction highlights the potential of tDCS in influencing and understanding brain functionality and cognitive health.

Understanding Emotion Regulation Strategies and Its Neural Mechanisms

According to a functionalist and evolutionary perspective, emotions serve as a tool with significant and adaptive roles that affect decision-making, prepare individuals for 'fight or flight' responses, and facilitate social communication. Consistent with this perspective, the current understanding is that emotions are not fixed and automatic, but rather can be modulated through emotion regulation. The process of emotion regulation entails people controlling their feelings in order to perform properly in a variety of social contexts (Wheeler et al., 2017).

Emotion regulation is a complex and multidimensional structure. Therefore, the literature discusses and classifies emotion regulation strategies from various perspectives, including psychological, physical, cognitive, and developmental perspectives (Gyurak et al., 2011). Emotion regulation may occur automatically (implicit emotion regulation) or intentionally (explicit emotion regulation), according to the cognitive framework of emotion regulation. Explicit emotion regulation involves deliberate attempts to control emotional responses and requires close monitoring, whereas implicit emotion regulation originates spontaneously and has goals unrelated to conscious emotional response modification (Qiu et al., 2023).

According to Braunstein and colleagues (2017), the explicit and implicit strategies to emotion regulation are reinforced by one aspect that includes shifting the nature of the emotion regulation process from automatic to controlled. The study suggests four possible methods for emotion regulation: implicit-controlled, implicit-automatic, explicit-controlled, and explicit-automatic.

As mentioned earlier, explicitly controlled emotion regulation strategies entail conscious awareness and deliberate regulation. Within this framework, the literature has highlighted three distinct explicit emotion regulation strategies that have garnered researchers' interest. The first strategy is selective attention, which involves focusing on or shifting away from specific features of affective stimuli (Braunstein et al., 2017). Attentional states can influence what is attended to, which in turn can impact emotional states. However, individuals possess the ability to intervene in and regulate both processes to some degree. By employing motivational techniques and imparting instruction on emotion regulation strategies, individuals can successfully prioritize positive stimuli over negative ones, thereby promoting an increase in positive affect (Livingstone & Isaacowitz, 2017). The process of selective attention involves modulating activity in salience processing areas, such the amygdala, by means of dlPFC and ACC (anterior cingulate cortex) activation. The results of research on clinical attention training indicate that selective attention is a viable explicit method for emotional regulation The studies illustrate that the implementation of this strategy can lead to increased activation of the prefrontal cortex (PFC), while simultaneously decreasing activation in regions linked to salience processing (Sean et al., 2017).

Distraction is the second explicit emotion regulation strategy that has received attention (Braunstein et al., 2017). Distraction is a technique for controlling emotions that entails concentrating on various elements of a circumstance or turning one's whole attention to something else (Kobayashi et al., 2021). Studies have documented activation in the dlPFC, vlPFC and right insula during the regulation of emotions through distraction. Previous research has demonstrated that these brain regions can modulate the activity of the amygdala or insula, which are regions involved in emotion generation, through cognitive emotion regulation (Jentsch et al., 2019).

Cognitive reappraisal is the third commonly employed explicit emotion regulation strategy (Braunstein et al., 2017). Reassessing a scenario and its importance in order to control emotions is known as cognitive reappraisal. Given the use of this technique, people can reframe events such that the emotional effect of the situations is reduced or altered. Cognitive reappraisal is frequently utilized as a means to mitigate negative affect. However, it can also serve to amplify positive affect or sustain neutral emotional states (Walker et al., 2022). The predominant focus of research on the neural networks and neurobiology underlying explicit emotion regulation stems from investigations into the reappraisal technique (Braunstein et al., 2017). One section of the neural networks engaged in cognitive reappraisal is the extensive cortical-subcortical network. Collectively, the frontal and parietal regulatory regions decrease activity in important subcortical emotion processing regions, such the amygdala. According to research, during cognitive reappraisal, specific brain regions are frequently activated. These regions include the dorsolateral prefrontal cortex (dlPFC), ventromedial prefrontal cortex (vmPFC), ventrolateral prefrontal cortex (vlPFC) and dorsal anterior cingulate cortex (dACC) (Steward et al., 2020). The dlPFC is essential for executive function because it enables the active processing of information required to reevaluate emotional stimuli. In a comparable manner, response selection and the suppression of emotional responses are crucial functions of the vlPFC and right dlPFC (Picó-Pérez et al., 2019). This inhibitory control is essential for overcoming the natural desire to evaluate a stimulus negatively when reappraising a highly stimulating stimulus (Silvers et al., 2014). The dACC and nearby dmPFC are activated by distraction and reappraisal. These areas keep an eye out for discrepancies between desired and actual behavioral results, signaling when administration has to be adjusted accordingly. Reappraisal studies have associated the anterior regions of the dmPFC to mentalizing, which has been proposed to be a critical function. These studies support individuals in monitoring and reflecting on their own emotional states, as well as reflecting on and reinterpreting the mental states of external stimuli (Bachmann et al., 2018). Given its anatomical and functional closeness to subcortical regions involved in emotion generation, the vmPFC is crucial in controlling emotional response. The requirements made upon intrinsic (self-directed) and extrinsic (task-oriented) processing during emotion regulation alter vmPFC activity. The vmPFC is recognized for being essential in managing the transition from passive, self-focused processing to actively generating reappraisals of negative stimuli (Steward et al., 2020).

Based on the explicit emotion regulation framework developed by Braunstein and colleagues (2017), the explicit-controlled emotion regulation method is where these three explicit techniques belong in. Explicit-controlled emotion regulation actually refers to the explicit strategies of emotion regulation that are most frequently used in the literature. Explicit-automatic emotion regulation, on the other hand, bases control on automatic processes and has an explicit goal of regulating emotions. Despite being the least researched attempted of control in neuroscience, there is one behavioral phenomena that has been well examined: placebo effects. Placebo effects are the result of expecting or believing that something would work to alter a stimulus-response without the need for a bottom-up control mechanism (Guevarra et al., 2022). From a neurobiological standpoint, the administration of a placebo has been associated with heightened activity in various brain regions, including the ventral striatum OFC, dlPFC and vmPFC (Geuter et al., 2017). It is believed that activation in these brain areas supports the establishment of expectations linked to placebos as well as maintaining of contextual information. Furthermore, according to Braunstrein et al. (2017), placebo beliefs may also control other kinds of emotional reactions, such as disgust and the insula activity that occurs along with it.

This has been stated that implicit emotion regulation refers to affect modification techniques that are launched by implicit goals and carried out by more automated processes. Currently, there are two primary strategies for regulating implicit emotions. One of these is extinction learning (Braunstein et al., 2017). The situation in which acquired responses continue to occur following repeated exposure to a conditioned stimuli are referred to as extinction learning (Picó-Pérez et al., 2019). Extinction learning is implicit because it does not require conscious regulation of negative emotions (Silvers, 2020). The other implicit emotion regulation strategy is reinforcer revaluation. The phenomena known as "reinforcer revaluation" describes how a stimulus that formerly produced one result—a bigger reward, for example—now produces a new result—a smaller reward. The vmPFC and medial orbitofrontal cortex are implicated in processes related to extinction and reappraisal of reinforcers. The vmPFC serves as a central processing hub for the computation and revision of emotional significance, integrating data from diverse brain systems. The vmPFC integrates information regarding the current circumstances, objectives, motivational states, and past learning experiences to generate responses that are contextually suitable. The present approach offers an extensive overview of the expected emotional values associated with actions, stimuli, and outcomes (Braunstein et al., 2017).

These two implicit emotion regulation strategies are classified as implicit-automatic emotion regulation according to Braunstein et al. (2017). Braunstein et al. (2017) also define the implicit-controlled dimension in addition to these. Furthermore, they characterize the implicit-controlled dimension as a class of emotion regulation strategies involving controlled processes and an implicit emotion regulation goal. The psychological processes underlying implicit-controlled strategies consist of various combinations of goals and processes. The first type of regulation strategies involves incidental regulatory targets, where regulation is a byproduct of using metacontrol to perform another task. Examples of such strategies include those used in the emotional Stroop task and go-no go tasks. Studies that examined emotions in combination with various cognitive control tasks (such as emotional Stroop or go/stop task) and nested different tasks consistently showed brain activation in the dLPFC, IFG, ACC, and amygdala regions (Song et al., 2017). Studies have revealed alterations in rACC activation during the Emotional Stroop task. Increased activation of the rostral anterior cingulate cortex (rACC) when exposed to emotional distractors in this task is likewise linked to a decrease in dACC activity (Mohanty et al., 2007; Szekely et al., 2016; Zhu et al., 2018).

Strategies involving the application of externally generated and controlled processes belong under the second category of implicitly controlled strategies. Research on automatic goal pursuit and studies where a persistently active internal goal—like preserving correct emotional value representations—activates regulated mechanisms to update emotional responses are both significant in this context. Reversal learning is one case of this in action, when an organism follows up on the idea that one stimulus in a pair is first linked to a reward. However, this association is later reversed, requiring the organism to adjust its emotional values for both stimuli. Research on animal lesion suggests that reversal learning involves implicit regulation-like vmPFC-dependent value updating (Panayi & Killcross, 2018). Previous findings that vmPFC lesions impair reversal may result from damage to the transitional fibers connecting the amygdala and vlPFC. On the other hand automatic goal pursuit studies demonstrate that unconsciously activated external goals can guide subsequent behavior. There is limited literature on automatic goal pursuit tasks. However, research suggests that top-down control processes play a role in this task (Braunstein et al., 2017).

The Impact of tDCS on Emotion Regulation

The development of neurocognitive models of psychopathology as a result of extensive neuroimaging research has suggested possible targets for noninvasive neurostimulation methods like tDCS. In addition to their therapeutic applications, these techniques can serve as valuable tools in experimental research aimed at investigating the affective and cognitive consequences of manipulating activity in specific brain regions associated with emotion regulation (Clarke et al., 2020). Applying anodal and cathodal stimulation, which respectively up- and down-regulate cortical activity in the corresponding brain area, may be used to evaluate performance on cognitive tasks. Recent research on tDCS has explored how modifying cortical activity across various brain regions, including the PFC, influences attention, working memory, decision-making, inhibitory control, planning, and multitasking abilities (Nejati et al., 2018). Moreover, it has been utilized to ameliorate executive dysfunction in neuropsychiatric conditions typified by impaired executive functioning, including schizophrenia, addiction, anxiety-related disorders, depression, and attention deficit hyperactivity disorder (Molavi et al., 2020).

Although tDCS studies have focused on psychopathologies, these conditions were measured using tasks that also assessed emotion regulation strategies. Studies of this nature represent a considerable portion of the academic literature focused on exploring emotion regulation strategies through the application of tDCS. For example, in a research by Clarke et al. (2020), the effect of tDCS on attention bias to negative emotional content was assessed using an attentional probe task. The study found no effect of tDCS on attentional bias variability, although it did demonstrate that it reduced emotional reactivity. Nejati, Majidinezhad, et al. (2022b) contended that deficiencies in emotion regulation capacity contribute to the onset of psychopathological conditions. They employed the Emotional Go/No-Go, Emotional Stroop, and Emotional 1-Back tasks to investigate how tDCS optimized women with major depression's the ability to regulate their emotions. The study found that tDCS stimulation increased working memory and interference control while having no effect on reaction time. The study found that when presented faces were happy, working memory performance increased and interference control decreased. The tDCS stimulation appeared to accelerate interference control in neutral and depressed faces, according to the emotional Stroop test. Furthermore, compared to the sham stimulation, accuracy was greater in the neutral and pleased face conditions of both actual stimulation groups.

The aim of this systematic review is to evaluate the influence of tDCS on various previously delineated emotion regulation strategies, aiming to enrich the current literature on the efficacy of tDCS. The methodology section encompasses a table presenting the articles assembled for this review.

Method

The literature review conducted for this study involved a comprehensive search for relevant literature, followed by a rigorous review of the identified sources, a conformity check, and the subsequent reporting of the findings. The abstract, method, and results sections of the studies identified in the literature review using the keywords "tDCS," "emotion regulation," "implicit emotion regulation," and "explicit emotion regulation" in the Google Scholar, PubMed, Scopus and Web of Science databases were examined in detail between 2018-2024. The rationale for selecting this specific year range is to analyze the findings of recent articles. This choice aims to better understand and evaluate current trends, innovations, and ongoing scholarly debates within the literature. Full-text articles were assessed for eligibility based on the inclusion and exclusion criteria.

The findings of this examination were then used to select 20 studies from Table 1 for inclusion in the study. Extracted data included: author(s), year of publication, sample characteristics, study design, type and duration of tDCS intervention, emotion regulation strategy assessed, tasks used, main findings, and conclusions. Any discrepancies in data extraction were resolved through discussion.

This literature review encompasses both descriptive and experimental studies. Inclusion criteria included articles written in English, the application of tDCS, and the measurement of implicit or explicit emotion regulation strategies using a standardized task. Thesis studies and research proposals were excluded from the review.

A narrative synthesis of the included studies was conducted. Studies were grouped according to the type of emotion regulation strategy (implicit vs. explicit), the specific brain regions targeted by tDCS, and the tasks used to measure emotion regulation. The effects of tDCS on emotion regulation were summarized and compared across studies.

Figure 1

PRISMA Flow Diagram of Main Search Strategy and Article Selection for this Review

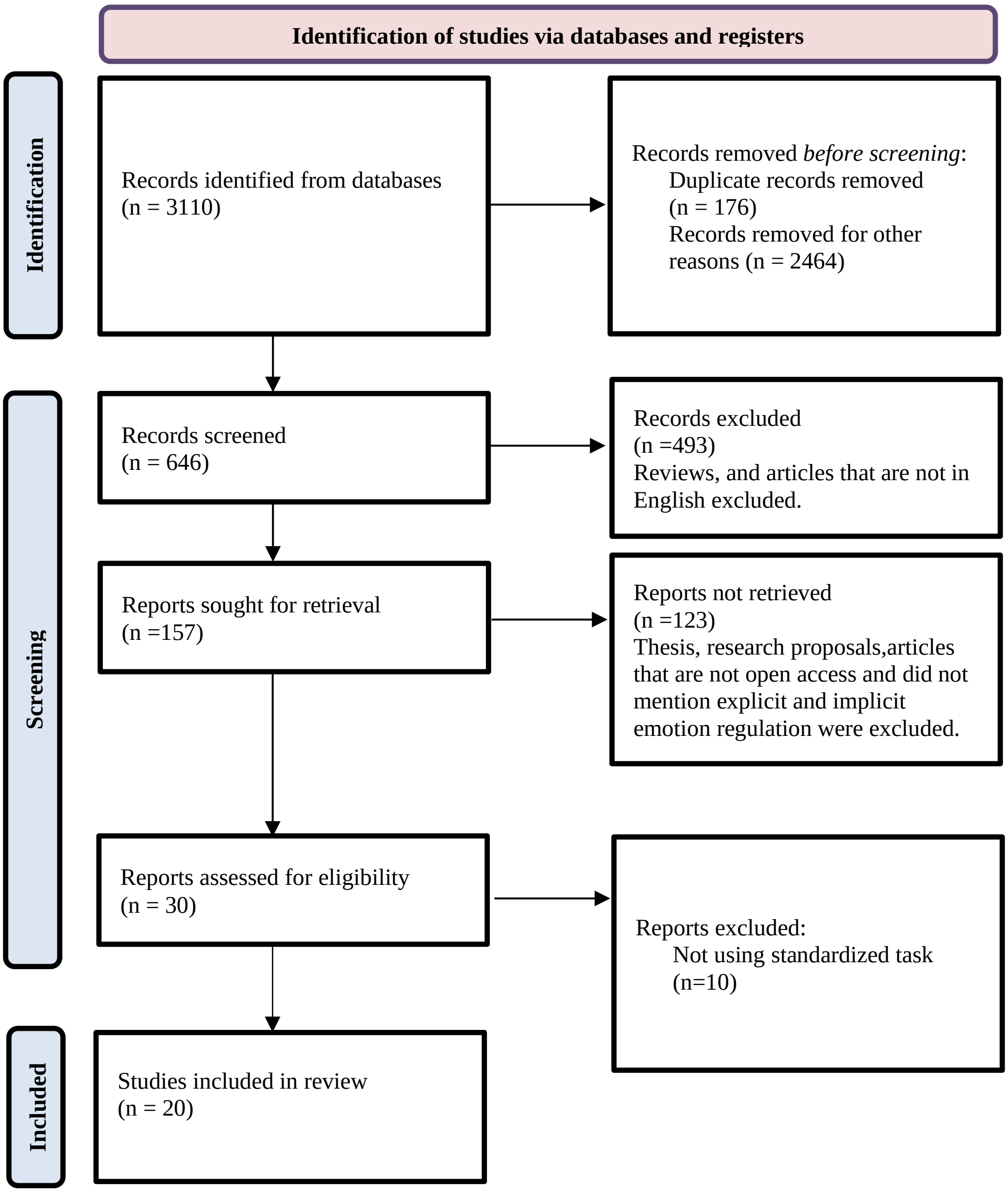

Table 1

Overview of the Studies Included in this Review

Author	ER goal and strategy	Task	tDCS application	Main findings
Chen et al. (2023)	Explicit/Cognitive reappraisal	Cognitive reappraisal task	Anodal DLPFC	The enhanced cognitive control functioned as a mediator in the impact of HD-tDCS on the modulation of reinterpretation, although it did not influence detachment.
Albein-Urios et al. (2023)	Explicit/Cognitive reappraisal	Cognitive reappraisal task	Anodal right VLPFC	Significant stimulation effects were observed in the 'Regulate' condition, revealing discrepancies in LPP amplitudes between anodal and sham stimulation.
De Smet et al. (2023)	Explicit/Cognitive reappraisal	Affective control task and Instructed reappraisal task	Cathodal and anodal right and left DLPFC	The findings showed that the emotional control task combined with active tDCS improved cognitive emotion regulation in participants.
Zhang et al. (2023)	Implicit/Implicit-controlled	Social exclusion pictures and priming words	Anodal rVLPFC and rDLPFC	Anode HD-tDCS stimulation of the rDLPFC and rVLPFC may considerably reduce the emotional reactions brought on by social isolation.
Smits et al. (2023)	Explicit/Cognitive reappsaisal	N-back task and Threat-of-Shock Paradigm	Anodal right DLPFC	This study did not identify any significant group-level distinctions between the sham and active tDCS training interventions.
Marotta et al. (2023)	Implicit/Implicit-controlled	Dot-probe task	Anodal right and left PFC	Right anodal-tDCS was found to eliminate the attentional bias (AB) toward angry faces and cause an AB toward sad faces in individuals with higher negative affect (NA) trait.
Nasiri et al. (2022)	Implicit and explicit/ Cognitive reappraisal and suppression	Go/Non-go task and N-back task	Cathodal DLPFC	Following treatment and at the 3-month follow-up, the group receiving UP combined with tDCS demonstrated notably greater enhancements in deficits related to emotion regulation, inhibition, and cognitive reappraisal.
Nejati, Majidinezhad, et al. (2022b)	Implicit/Implicit-controlled	Emotional go/no-go task and Emotional N-back task	Cathodal and anodal DLPFC and VMPFC	Anodal left dlPFC/cathodal right vmPFC stimulation improved interference control accuracy and speed.

Table 1 (Continued)

Author	ER goal and strategy	Task	tDCS application	Main findings
Doerig et al. (2021)	Explicit/Cognitive reappraisal	Cognitive reappraisal task	Anodal DLPFC	During the reappraisal phase, the application of anodal tDCS was observed to be linked with a notable decrease in negative valence.
Clarke et al. (2020)	Explicit/Cognitive reappraisal	Cognitive reappraisal task	Anodal left DLPFC	The evaluation of negative stimuli during emotion regulation was not affected by the use of tDCS.
Wu et al. (2020)	Explicit/Cognitive reappraisal	Cognitive reappraisal task	Anodal right DLPFC	In instances of craving and negative emotions, tDCS to the right dlPFC led to downregulation of craving and upregulation of negative emotions.
Clarke, Sprlyan, et al. (2020)	Explicit/Selective attention	Mindfulness task	Anodal left DLPFC	Active tDCS administration significantly increased anxiety in response to worry induction.
Hansenne and Emilie (2020)	Explicit/Cognitive reappraisal	Cognitive reapprasial task	Anodal left DLPFC	The application of anodal tDCS to the left DLPFC can serve as a method for augmenting emotion regulation, whether in response to negative or positive emotional stimuli.
Yan et al. (2020)	Implicit/Implicit-controlled	Subliminal go priming and dot-probe task	Cathodal left OFC	Cathodal stimulation induced priming of implicit control targets, leading to a decrease in attentional avoidance of fear stimuli.
He et al. (2019)	Explicit/Cognitive rappraisal	Cognitive reappraisal task	Anodal RVLPFC	tDCS activation of the RVLPFC demonstrates a more substantial regulatory impact on social exclusion compared to individual negative emotions.
Ganho-Ávila et al. (2019)	Implicit/Fear extinction	Fear conditioning procedure	Cathodal rDLPFC	One to three months after the tDCS session and extinction, the cathodal tDCS group exhibited a moderate safety learning effect in action tendencies toward neutral stimuli.
Zhang et al. (2019)	Explicit/Cognitive reappraisal	Cognitive reappsaisal task	Anodal rVLPFC	Participants with mild depression showed decreased negative affect ratings when anodal tDCS was applied to the rVLPFC.
He et al. (2018)	Implicit/Cognitive reappraisal	Cognitive reappraisal task	Anodal rVLPFC	During reappraisal, anodal tDCS to the rVLPFC reduced pupil diameter and negative emotion evaluations.
Marques et al. (2018)	Explicit/Cognitive reappraisal	Cognitive reappraisal task	Anodal DLPFC and anodal VLPFC	tDCS targeting the VLPFC led to a decrease in the negative valence of negative images and a reduction in the cardiac beat interval during an earlier stage of emotional processing.
Sánchez-López et al. (2018)	Implicit/Implicit-controlled	Attentional engagement-disengagement task	Anodal left DLPFC and right DLPFC	Active tDCS stimulation of the right DLPFC delayed gaze separation from emotional faces, whereas left DLPFC stimulation accelerated it.

Discussion

Table 1 presents a list of research articles that fit the inclusion criteria established through the literature review process. These 20 studies measured implicit or explicit emotion regulation strategies using the appropriate tasks. Upon initial examination, it becomes evident that explicit emotion regulation studies have been more extensively investigated than implicit emotion regulation studies (Albein-Urios et al., 2023; Chen et al., 2023; Clarke et al., 2020; Doerig et al., 2021; Hansenne and Emilie, 2023; He et al., 2018; He et al., 2019; Marques et al., 2018; Wu et al., 2020; Zhang et al., 2019)This difference could stem from the inherent complexity and difficulty involved in directly assessing implicit emotion regulation strategies through tasks. On the other hand, the lack of a distinct demarcation between implicit and explicit emotion regulation strategies could have influenced the observed distinctions. Implicit emotion regulation involves automatic and unconscious processes that modulate emotional responses, whereas explicit emotion regulation entails deliberate and conscious efforts to regulate emotions (Qiu et al., 2023). The challenge in studying implicit emotion regulation lies in the development of tasks that can accurately capture these processes. Numerous traditional emotion regulation tasks predominantly evaluate explicit strategies like cognitive reappraisal or expressive suppression, which are more straightforward to gauge through self-report or observable behavioral responses. However, recent advancements in experimental paradigms, such as implicit association tasks and physiological measures, offer promising avenues for directly investigating implicit emotion regulation (Etkin et al., 2020).

Upon reviewing numerous studies on this topic, it becomes evident that tDCS administration enhances both implicit and explicit emotion regulation performance (Albein-Urios et al., 2023; Chen et al., 2023; Clarke, Sprlyan, et al., 2020; De Smet et al., 2023; Doerig et al., 2021; Ganho-Ávila et al., 2019; Hansenne and Emilie, 2023; He et al., 2018; He et al., 2019; Marques et al., 2018; Marotta et al., 2023; Nasiri et al., 2022; Nejati, Majidinezhad, et al., 2022b; Sánchez-López et al., 2018; Wu et al., 2020; Yan et al., 2020; Zhang et al., 2019; Zhang et al., 2023). However, studies by Smits et al. (2023) and Clarke et al. (2020) did not detect a significant influence of tDCS on emotion regulation, despite the majority of research suggesting otherwise. This disparity in the literature suggests that research on tDCS have not clearly shown whether tDCS has an impact. The overarching conclusion derived from this is the necessity for an expansion of studies evaluating the effects of tDCS on emotion regulation, employing diverse combinations of variables.

Regional specificity emerged as a key theme across the reviewed studies, with various regions of the PFC targeted in tDCS interventions. Anodal stimulation of the DLPFC, for instance, consistently yielded enhancements in explicit cognitive reappraisal abilities (Chen et al., 2023; Hansenne & Emilie, 2023), whereas stimulation of the VLPFC showed promise in modulating emotional valence (Marques et al., 2018). However, methodological variability in stimulation parameters and task designs complicates the interpretation of findings and underscores the need for standardization in future research.

Moreover, individual differences in baseline cognitive and emotional functioning as well as trait characteristics may moderate tDCS effects of tDCS on emotion regulation. For example, individuals with heightened levels of negative affect or depression may exhibit differing levels of responsiveness to tDCS interventions targeting emotion regulation enhancement (He et al., 2018; Zhang et al., 2019). Understanding these individual differences is crucial for tailoring tDCS interventions to specific populations and optimizing the treatment outcomes.

In summary, the majority of evidence indicates that tDCS improves emotion regulation; yet, inconsistent results emphasize the need for more study to clarify the exact processes behind these improvements. To optimize the therapeutic efficacy of transcranial magnetic stimulation (tDCS) for enhancing adaptive emotion regulation and psychological well-being, forthcoming research should focus on elucidating the impact of location-based specificity, individual differences, and methodological factors on tDCS outcomes.

It is an undeniable reality that stressful life events and conflicts are inevitable incidents that can induce changes in an individual's mood. While minor mood fluctuations are inherent to life, enduring and substantial mood disruptions can elevate stress levels and profoundly affect an individual's quality of life (Çınaroğlu, 2024). Thus, through elucidating the effects of tDCS on emotion regulation in both clinical and non-clinical populations, along with understanding the underlying mechanisms, we can optimize its therapeutic potential to improve cognitive and emotional well-being. In conclusion, this systematic review emphasizes the requirement for additional studies exploring the effects of tDCS on emotion regulation across explicit and implicit dimensions. Future research requires to examine individual variations in response to tDCS treatments and clarifies the underlying brain processes of tDCS-induced modifications in emotion regulation.

Consequently, tDCS represents a potentially powerful tool for investigating and modulating cognitive function and emotion regulation processes. By integrating insights from neuroscience and psychology, tDCS research offers valuable insights into the complex interplay between brain function and emotional regulation. This paves the way for innovative interventions designed to improve mental health and overall well-being.

Compliance with Ethical Standards

Ethical Approval

Ethical committee approval for this study is not applicable.

Author Contributions

All authors participated equally in all aspects of the preparation of the review article, with each contributing 50% of the total effort.

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