

REVIEW

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The modulating effects of brain stimulation on emotion regulation and decision-making

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Abstract

Background: It has been reported that brain stimulation such as repetitive transcranial magnetic stimulation (rTMS) and transcranial direct current stimulation (tDCS) can modulate a variety of cognitions and emotions in humans. rTMS and tDCS studies provide strong possibilities of applications in the manipulation of emotion regulation and decision-making in humans.

Methods: We searched the literature by using keywords “rTMS,” “tDCS,” “emotion regulation,” and “decision-making” on PubMed (<http://www.ncbi.nlm.nih.gov/pubmed>). Based on the search results, we reviewed studies on emotion regulation and decision-making using rTMS and tDCS modulations.

Results: Regarding emotion regulation, rTMS can influence both attentional and affective aspects of emotion regulation. tDCS studies for emotion regulation included diverse topics such as physiological arousal, social exclusion, mathematics anxiety, emotional reactions to pain stimuli, negative affect, momentary ruminative self-referent thoughts, and autonomic reactions to affective pictures. Decision-making studies have reported rTMS effects related to emotion such as delay-discounting tasks, food choice, and moral judgment. These studies have also investigated cognitive functions such as visuospatial attention, perception, object identification, spatial-working memory, visuomotor skills, task, and blameworthiness and punishment decisions. In tDCS studies for decision-making, it has increasingly been reported that tDCS influences moral judgment, risk-taking behaviors, choice modulation, delay discounting, maladaptive and perceptual decision-making, probabilistic guessing, perception of space and time, dual-task performance, model-based learning, addiction, food craving, sunk-cost effect, exploration-exploitation trade-offs and cognitive impulse control.

Conclusion: rTMS and tDCS have been shown to modulate behaviors relevant to emotion regulation and decision-making. The results of these numerous studies can be applied to clinical populations, and demonstrate that rTMS and tDCS may have many beneficial implications to those who have emotion regulation deficiencies.

Keywords: rTMS, tDCS, Emotion regulation, Decision-making, Neuromodulation

Background

Emotion regulation and decision-making play an important role in human behaviors relevant to adaptation and problem solving. Cognition is related to processes including attention, memory, language, and problem-solving; whereas emotion has various characteristics such as states caused by rewards and punishments, conscious or unconscious evaluations of events, and basic affects such as fear and anger, according to past researchers [43]. Cognition and emotion are essential to emotion regulation and decision-making in various aspects and dimensions. According to Ochsner's recent model [53], generation, self-report, perception, and regulation of emotions are based on the interactions between cognition and emotion. However, emotion regulation is different from others in that it has up-and-down-regulatory effects of emotion [53]. Decision-making consists of processes of encoding preferences, selecting and executing actions, and evaluating outcomes. These processes can be divided into input, process, output, and feedback [16].

Both emotion regulation and decision-making influence human behavior by top-down or bottom-up processing in the brain [44]. According to the interactive influence model of emotion and cognition, cognition interacts with emotion in both decision-making and emotion regulation. For example, decision-making is influenced by bottom-up processing such as increasing emotional reaction and decreasing cognitive capacity; it is further influenced by top-down processing such as regulating emotional responses by cognitive strategy [44]. Regarding the functional anatomy of the brain, emotion regulation and decision-making share dorsomedial, dorsolateral, ventrolateral, and medial regions of the prefrontal cortex [48]. Due to the anatomical characteristics of emotion regulation and decision-making, brain stimulation to these areas using rTMS and tDCS can influence emotion regulation and decision-making by modulating the interaction in the brain circuits.

Recently, it has been reported that brain stimulation such as repetitive transcranial magnetic stimulation (rTMS) and transcranial direct current stimulation (tDCS) can modulate a variety of cognitions and emotions in humans through experimental and clinical perspectives [32]. Past rTMS and tDCS studies have reported strong potentials for applying these different brain stimulations as a way to manipulate emotion regulation and decision-making in humans.

In this paper, we review the application of rTMS and tDCS on human emotion regulation and decision-making in experimental studies published thus far, as well as suggest future directions for tDCS and rTMS in emotion regulation and decision-making.

Review

Methods

We searched the literature by keywords "rTMS," "tDCS," "emotion regulation," and "decision-making" on PubMed (<http://www.ncbi.nlm.nih.gov/pubmed>). We reviewed studies on emotion regulation and decision-making using rTMS and tDCS modulations. In addition, we suggested clinical applications of rTMS and tDCS relevant to emotion and cognition for future studies. We collected papers that were published no later than December 2015.

Neuronal mechanisms of rTMS and tDCS

The effects of TMS are largely divided into two kinds based on the methods of stimuli applied. First, single- and paired-pulse TMS induce neurons to depolarize and discharge

an action potential. These phenomena can be identified through changes in motor-evoked potentials on electromyography of the primary motor cortex or phosphenes in the occipital cortex when TMS is applied [54]. Second, rTMS applied to the cortex through repeated stimuli causes relatively long-term effects beyond the duration of stimuli. rTMS increases or decreases excitability of the corticospinal tract according to the intensity of stimuli, the direction of the coil, and the frequency used [65, 73]. High frequency (HF) (5–20 Hz) rTMS increases cortical response, which is identified by a reduced motor-evoked potential threshold [2, 55]. Low frequency (LF) (≤ 1 Hz) rTMS inhibits the cortical response [11] (Fig. 1). Recently, some studies demonstrated that the HF and LF rTMS induce neuronal plasticity [14, 40, 45, 74, 85, 86].

tDCS is based on the principle that the anode (positively-charged electrode) enhances cortical excitability, whereas the cathode (negatively-charged electrode) reduces it (Fig. 1). Anodal tDCS increases the neuronal excitability and cathodal tDCS decreases the neuronal excitability [50, 51]. A tDCS-positron emission tomograph (PET) study for the primary motor hand area showed that anodal tDCS increased regional cerebral blood flow in many cortical and subcortical regions compared to cathodal tDCS, while cathodal tDCS increased only the left dorsal premotor cortex [38]. tDCS's excitatory effect maintains up to 90 min [50]; however, daily repetitive tDCS has been shown to cause prolonged effects [1]. tDCS delivers a constant, weak, direct current to the region of the brain which is being stimulated. The efficacy of tDCS depends on current density and stimulation duration, which determine the induced electrical field strength and the occurrence and duration of after-effects, respectively [49]. Direct currents have generally been delivered via a pair of sponge electrodes moistened with tap water or sodium chloride (NaCl) solution (size between 25 and 35 cm²), and the current density delivered has varied between 0.029 and 0.08 mA/cm² [49].

rTMS and tDCS in emotion regulation and decision-making

Emotion regulation

rTMS

Recently, rTMS has been applied to emotion regulation, albeit studies are few thus far (Table 1). Vanderhasselt et al. [75] measured attentional processing of threatening information by HF rTMS over the right dorsolateral prefrontal cortex (DLPFC), using an emotional modification of the exogenous cueing task [58]. Individuals who scored higher on self-reports of state anxiety during baseline were more attentionally biased toward negative information after HF rTMS. In addition, state anxiety prior to stimulation correlated positively with induced attentional bias. Another study [15] investigated the effects of HF rTMS over the right or left DLPFC on the attentional processing of

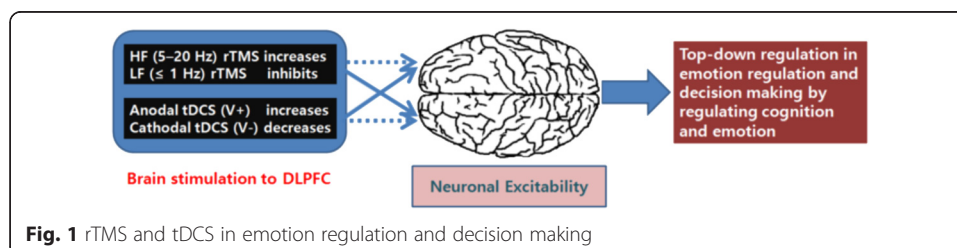


Fig. 1 rTMS and tDCS in emotion regulation and decision making

Table 1 rTMS and tDCS studies in emotion regulation

Authors	Target of study	Subjects/Design	Region stimulated/Frequency (rTMS)/Intensity/Duration	Results
rTMS				
Berger et al. 2015 [3]	Autonomic reactions to affective pictures	F40/Crossover design (with an interval of 2 weeks once with a real rTMS and once with a sham rTMS)	R DLPFC/one session of LF rTMS (1 Hz) or one session of HF rTMS (10 Hz), and sham stimulation/10 Hz rTMS impulse train lasted 5 s, with an inter stimulus-interval of 10 s, and included 18 trains with 900 pulses in total, and had an overall duration of 4.5 min. The 1 Hz rTMS was applied continuously for 15 min with 900 pulses in total.	The LF rTMS increased heart rate deceleration for negative and neutral pictures, compared to positive pictures. However, the HF rTMS did not influence the cardiac orienting response to picture valence and arousal.
De Raedt et al. 2010 [15]	Attentional aspect of emotion regulation	F18 + F19/Combination of single-blind randomized crossover within-subjects design (HF-rTMS - L DLPFC and sham stimulation ($n = 18$), one week's time interval) and between-subjects design (HF-rTMS - R DLPFC ($n = 19$), compared to the sham condition of HF-rTMS - L DLPFC)	R or L DLPFC/HF (10 Hz) rTMS and sham/ Stimulation intensity of 110 % of the subject's motor threshold/40 trains of 3.9s duration, separated by an intertrain interval of 26.1s (1560 pulses per session).	R prefrontal HF rTMS delayed disengagement from angry faces.
Schutter and van Honk, 2009 [68]	Mood in emotion regulation	F12/Single-blind, sham and occipital-controlled crossover design,	Cerebellar, occipital, or sham stimulation (on three separate days)/LF (1 Hz) rTMS/ Stimulation intensity: 45 % of maximum machine output/for 20 min	Cerebellar rTMS increased negative mood after an emotion regulation task for aversive and neutral scenes.
Vanderhasselt et al. 2011 [75]	Attentional aspect of emotion regulation	F28/Sham (placebo-)controlled, double blind crossover design	R DLPFC/HF (10 Hz) rTMS and sham/Stimulation intensity: 110% of the motor threshold (MT). 40 trains of 3.9 s duration, separated by an intertrain interval of 26.1 s (1560 pulses per session). The total stimulation time was approximately 20 min.	Higher baseline self reported state anxiety scores showed greater attentional biased toward negative information after HF rTMS.
Zwanzger et al. 2014 [87]	Affective processing of emotional stimuli	40 (F23)/Sham-controlled, between-subject design	R DLPFC/LF (1 Hz) rTMS and sham/Stimulation intensity of 120 % related to the individual motor threshold/for 30 min	Increased activation for fearful faces compared to neutral faces in the right temporal parietal junction (TPJ) region between 110 and 170 ms.

Table 1 rTMS and tDCS studies in emotion regulation (*Continued*)

tDCS				
Feeser et al, 2014 [20]	Arousal during emotion regulation	48 (F25)/Double-blind, between-subjects design	Anodal tDCS - R DLPFC (F4), Cathode tDCS - L supraorbital region. 1.5 mA for 20 min. Applied during the emotion regulation task and started 4 min before the task.	During down regulation decreased skin conductance responses (SCR) and emotional arousal ratings. During up regulation increased arousal ratings and SCR
Peña-Gómez et al. 2011 [56]	Negative affect for negative stimuli	F16/Randomized, sham-controlled, crossover trial	DLPFC/L anodal (F3)/R cathodal (C4) and sham tDCS/1 mA for 20 min.	Decreased negative affect for negative stimuli, while higher introversion personality dimension scores produced an increased effect
Pripfl and Lamm 2015 [59]	Negative affect for negative pictures	17 smokers (F11)/Within-subjects design	DLPFC/L anodal, R anodal, and sham stimulation A direct current of 0.45 mA intensity (anodal current density: 0.085 mA/cm ²) for 15 min	R anodal tDCS - DLPFC decreased negative affect for negative pictures
Rêgo et al. 2015 [62]	Pain stimuli	24 (M12)/Double-blinded, randomized, sham-controlled study.	DLPFC/L anodal/R cathodal, L cathodal/R anodal, and sham tDCS/2 mA/tDCS started 5 min prior to the experimental task, and throughout the entirety of the task (a total of approximately 15 min of stimulation)	L cathodal/R anodal, tDCS decreased valence and arousal evaluations compared to other tDCS conditions. Both left-cathodal/right-anodal and left-anodal/right-cathodal tDCS decreased self-pain perception, hostility and sadness compared to sham condition
Riva et al. 2015a [63]	Regulation of negative emotions (social exclusion)	80 (F63)/Between-subjects design	Anodal tDCS or sham stimulation - rVLPFC, reference (cathodal) electrode - contralateral supraorbital area. 1.5 mA for 20 min	Reduced behavioral aggression
Riva et al. 2015b [64]	Regulation of negative emotions (social exclusion)	82 (F50) - Exp1 & 40 (F25) - Exp2/ Double-blind, between-subjects design	Exp1: Cathodal tDCS (rVLPFC) or sham, reference (anodal) electrode - contralateral supraorbital area. Exp2: Cathodal tDCS (R posterior parietal cortex), reference (anodal) electrode - contralateral supraorbital area. 1.5 mA for 20 min	Cathodal tDCS of rVLPFC increased negative emotional reactions brought out by social exclusion
Sarkar A, et al. 2014 [67]	Mathematics anxiety	High mathematics anxiety group (25 (M10)) & Low mathematics anxiety group (20 (F13))/Double-blind, placebo-controlled, crossover design	DLPFC/L anodal/R cathodal tDCS and sham stimulation/1 mA for 30 min	Compared to sham stimulation, high mathematics-anxiety individuals showed reduced RT on simple arithmetic decisions and cortisol concentrations;

Table 1 rTMS and tDCS studies in emotion regulation (*Continued*)

Vanderhasselt et al. 2013 [76]	Momentary ruminative self-referent thoughts	32 (F20)/Sham controlled within subjects study. An interval of at least 48 h.	DLPFC/L anodal (F3)/R cathodal (supra orbital area) and sham tDCS/2 mA for 20 min	however, compared to sham stimulation, low math anxiety subjects showed decreased RT and cortisol concentration. Reduced momentary ruminative self-referent thoughts were reported from subjects updating and shifting from angry faces to neutral faces
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R right, *L* left, *M* male, *F* female

emotional information using an emotional modification of the exogenous cueing task during fMRI. Right prefrontal HF rTMS delayed disengagement from angry faces, decreased activation of the right DLPFC, dorsal anterior cingulate cortex (dACC) and left superior parietal gyrus; and increased activation of the right amygdala. Left prefrontal HF rTMS, on the other hand, diminished attentional engagement of angry faces and was associated with increased activity within the right DLPFC, dACC, right superior parietal gyrus and left orbitofrontal cortex. This demonstrates that HF rTMS modulates aspects of attention and related brain activations differently according to the regions of the frontal cortex stimulated.

LF (inhibitory) rTMS applied to the right DLPFC was reported to modulate early affective processing [87]. The study measured MEG activation for fearful and neutral faces as well as gender discrimination before and after rTMS. Results showed increased activation for fearful faces compared to neutral faces in the right temporal parietal junction (TPJ) region between 110 and 170 ms. Berger et al. [3] studied autonomic reactions to affective pictures using LF rTMS (1 Hz) or HF rTMS (10 Hz) over the right DLPFC, compared to a sham stimulation. The LF rTMS increased heart rate deceleration for negative and neutral pictures compared to positive pictures. However, the HF rTMS did not influence the cardiac orienting response to picture valence and arousal. Schutter and van Honk [68] studied cerebellar function related to emotion regulation using LF rTMS. They demonstrated that LF rTMS to the cerebellum increased negative mood after an emotion regulation task for aversive and neutral scenes, indicating the importance of the cerebellum in emotion regulation. This demonstrates that LF rTMS to the DLPFC or cerebellum modulates emotion regulation related to affective processing.

In summary, rTMS can influence attentional aspects of emotion regulation [15, 75], affective processing of emotional stimuli [87], and autonomic reactions to affective pictures [3]. Also, these studies show that rTMS applied to the cerebellum can affect mood in emotion regulation [68].

tDCS

tDCS also has been applied to emotion regulation (Table 1). According to a study of tDCS's effects on the cognitive regulation of negative emotions using reappraisal instructions [52], anodal tDCS of the right DLPFC (F4 of the 10-20 international system) with cathode over the left supraorbital region during down regulation decreased skin conductance responses (SCR) and emotional arousal ratings when compared to a sham stimulation. However, anodal tDCS of the same region during up regulation increased arousal ratings and SCR [20]. These results reflect that the sympathetic nervous systems involved in arousal is modulated by stimulating the DLPFC. In addition, negative emotional reactions to social exclusion are related to right ventrolateral prefrontal cortex (rVLPFC). According to the literature, only two social exclusion studies using tDCS have been performed. The first study either socially excluded, or included, participants during anodal tDCS or sham stimulation, which was applied to the rVLPFC. After receiving stimulation, participants were given an opportunity to take out their aggression. The excluded participants who received anodal tDCS over the rVLPFC demonstrated reduced behavioral aggression compared to the sham stimulation condition, as well as equal levels of aggressive behaviors as those participants in the included condition [63]. The same research group conducted a second study on social exclusion using

tDCS. Their findings showed that cathodal tDCS over the rVLPFC increased negative emotional reactions brought on by social exclusion, confirming that rVLPFC plays an important role in regulating negative emotions [64].

In a study on mathematics anxiety in healthy subjects using tDCS and salivary cortisol, Sarkar et al. [67] expected that anodal stimulation to the left DLPFC and inhibitory cathodal stimulation to the right DLPFC would produce the greatest reduction in negative emotional reactions. The authors based this on previous studies related to salivary cortisol [8] and positive and negative emotional processing of the left and right DLPFC ([31, 78]. Their results showed that real tDCS applied to the DLPFC reduced reaction time (RT) on simple arithmetic decisions and cortisol concentrations compared to sham stimulation in high mathematics-anxiety individuals. However, this stimulation did not decrease RT and cortisol concentration compared with sham stimulation in low mathematics-anxiety individuals.

Rêgo et al. [62] assessed emotional reactions to pain stimuli before and after tDCS to the DLPFC and compared the effects of left anodal/right cathodal, left cathodal/right anodal, and sham conditions. Left cathodal/right anodal tDCS decreased valence and arousal evaluations when compared to the other tDCS conditions. The results of this study also showed that both left cathodal/right anodal and left anodal/right cathodal tDCS decreased the perception of pain in participants, as well as decreased hostility and sadness when compared to the sham condition; however, there were no significant differences between the active tDCS conditions. Thus, these results suggest that stimulating the DLPFC modulates valence, arousal, and perception of pain stimuli.

A tDCS study of smokers showed that anodal tDCS over the right DLPFC decreased negative affect for negative pictures when compared to a sham condition, and left anodal stimulation when appraising smoking cues related to cigarettes, neutral, negative, and positive pictures [59]. In a study using anodal tDCS over the left DLPFC, researchers showed that participants decreased their negative affect for negative stimuli. This effect was higher in subjects who reported higher scores on the introversion personality dimension [56]. Vanderhasselt et al. [76] found that anodal tDCS of the left DLPFC did not directly influence momentary ruminative self-referent thoughts, but that the effects of tDCS were mediated indirectly by emotional working memory for angry faces. The researchers concluded that subjects who were better at shifting from angry faces to neutral faces reported less momentary ruminative self-referent thoughts after tDCS. Therefore, negative affect for negative stimuli as well as ruminative thoughts are modulated by tDCS to the DLPFC, indicating that brain stimulation may regulate emotion.

In summary, tDCS studies for emotion regulation investigated thus far are more diverse than rTMS studies. These studies show that, depending on the stimulated brain regions, anodal tDCS influences arousal during emotion regulation [20], regulation of negative emotions in situations characterized by social exclusion [63, 64], mathematics anxiety [67], emotional reactions to pain stimuli [62], negative affect for negative pictures [59], negative affect for negative stimuli [56], and momentary ruminative self-referent thoughts [76].

Decision-making

rTMS

rTMS studies have been published which investigate decision-making in relation to emotion (Table 2). Responses to rewards can be modulated by stimulating the medial

Table 2 rTMS and tDCS studies in decision making

Authors	Target of study	Subjects/Design	Region stimulated/Frequency (rTMS)/Intensity/Duration	Results
rTMS				
Buckholtz et al. 2015 [9]	blameworthiness and punishment decisions	66 (M32)/2 x 2 between-groups design, with rTMS condition (active versus sham) and hemisphere (left versus right DLPFC) as between-subject factors.	R or L DLPFC/1 Hz rTMS stimulation and sham. The maximum stimulation duration in any one session was approximately 30 min, constraining each of the two rating sessions to 15 min. The two sessions were separated by no less than 48 hr and no more than 2 weeks.	LF rTMS over DLPFC lowered punishment for culpable acts, but did not affect blameworthiness judgments.
Camus et al. 2009 [10]	food choice	56 (M30) - Exp1 & 15 (M8) - Exp 2	R DLPFC/1 Hz-rTMS/Two control groups (1 Hz-rTMS - vertex and sham)/Stimulation intensity: 50 % of the stimulator maximum. A single, 15 min, 1 Hz rTMS train (900 pulses). 1st control group (15 min, 1 Hz rTMS train at 50% of the stimulator maximum). 2nd control group - sham rTMS over the right DLPFC,	1 Hz-rTMS to the R DLPFC decreased values assigned to food stimuli
Cho et al. 2015 [13]	delay discounting	24 (F11)/Within-subject design	MPFC and vertex stimulation (control condition)/10 Hz-rTMS. Stimulus intensity: 80% of the active motor threshold/Applied during the behavior study with the delay discounting task	10 Hz-rTMS to the MPFC increased the preference toward delayed larger-size rewards and decreased the choices for immediate small-size rewards.
Gongora et al. 2016 [25]	visuomotor task involving decision making	12 (M4)	Superior Parietal Cortex (SPC; Brodmann area 7)/1 Hz – 15 min – 80 % Resting Motor Threshold (15 min)	Absolute beta power decreased in Fp1 and increased in Fp2 at rest before task, but Fp2's absolute beta power increased during the task, and F4's absolute beta power decreased, and F7's absolute beta power increased during the task and decreased at rest after task. The parietal regions (P3, Pz and P4)'s absolute beta power decreased during the visuomotor task, compared to rest conditions.
Ishibashi et al. 2011 [33]	function and manipulation tool knowledge	13 (F6)	L lateral ATL and L IPL, occipital pole (control site)/Inhibitory rTMS/Stimulation was delivered at 120 % of motor threshold but kept at 67 % of the device's maximum output if it exceeded this criterion (This occurred in 16.7 % of the sessions). Average stimulation	Inhibitory rTMS to L lateral ATL increased RT for the "function" judgments, whereas inhibitory rTMS of L IPL increased RT for the "manipulation" judgments.

Table 2 rTMS and tDCS studies in decision making (Continued)

Koch et al. 2005 [36]	spatial working memory	9 (F4)	intensity was 58.8%. Participants received 10-min of TMS stimulation (1 Hz for 600 s).	R posterior parietal cortex (PPC), R premotor cortex (SFG), and R DLPFC/HF rTMS (25 Hz)/rTMS trains of eight stimuli at 25-Hz frequency (mean stimulation time: 300 ms) were delivered at an intensity of 110 % of motor threshold	Both HF rTMS - R posterior parietal cortex (PPC) and R DLPFC increased RT during the delay phase (no effect observed for R SFG). HF rTMS - R DLPFC increased RT selectively during the decision phase
Philiastides et al. 2011 [57]	perception	12 (F8)	L DLPFC/LF rTMS and sham/Stimulation intensity: 110% of motor threshold/Two separate 12 min rTMS sessions: a 1 Hz LF rTMS to the L DLPFC and a 12 min sham rTMS over the same area	L DLPFC/LF rTMS and sham/Stimulation intensity: 110% of motor threshold/Two separate 12 min rTMS sessions: a 1 Hz LF rTMS to the L DLPFC and a 12 min sham rTMS over the same area	Decreased accuracy and increased RT
Sheffer et al. 2013 [69]	delay discounting	47 smokers & 19 nonsmokers/Single-blind, within-subjects design	L DLPFC/Three sessions of HF rTMS (20Hz, 10 Hz, sham)/900 pulses of HF rTMS (20 Hz, 10 Hz, sham) separated by at least 48 hours - 20 Hz & 10 Hz (110 % MT, 1 second on, 20 seconds off), sham (10 Hz, 1 second on, 20 seconds off, 5.5 mA)	L DLPFC/Three sessions of HF rTMS (20Hz, 10 Hz, sham)/900 pulses of HF rTMS (20 Hz, 10 Hz, sham) separated by at least 48 hours - 20 Hz & 10 Hz (110 % MT, 1 second on, 20 seconds off), sham (10 Hz, 1 second on, 20 seconds off, 5.5 mA)	HF rTMS to the L DLPFC decreased discounting of monetary gains and increased discounting of monetary losses in both smokers and nonsmokers, but had no effect on cigarette consumption in smokers
Studer et al. 2014 [71]	visuospatial attention	28 (M15)/Within-subject design (separated by 6–8 days)	Inhibitory cTBS - AG bilaterally, cTBS - PMC bilaterally (active control condition) and without stimulation/ Consisting of bursts of three pulses at 50 Hz repeated at 5 Hz for 30 s (450 pulses) per hemisphere. Stimulation intensity: 40 % of maximum machine output.	Inhibitory cTBS - AG bilaterally, cTBS - PMC bilaterally (active control condition) and without stimulation/ Consisting of bursts of three pulses at 50 Hz repeated at 5 Hz for 30 s (450 pulses) per hemisphere. Stimulation intensity: 40 % of maximum machine output.	cTBS - AG affects decision-making tasks requiring visuospatial attention by disrupting the relationship between decision latencies and the probability of winning/losing.
Tassy et al. 2012 [72]	moral judgment	24	R DLPFC/1 Hz-rTMS (a single, 15-min, 900 pulses) or sham/Stimulation intensity: 54 % of the stimulator maximum output	R DLPFC/1 Hz-rTMS (a single, 15-min, 900 pulses) or sham/Stimulation intensity: 54 % of the stimulator maximum output	1 Hz-rTMS to the R DLPFC increased utilitarian responses during objective evaluation of moral dilemmas,
Viggiano et al. 2008 [77]	object identification	39 (F25)	No rTMS (baseline), real rTMS (L DLPFC), real rTMS (R DLPFC), and sham rTMS (L DLPFC)/10 Hz-rTMS/An intensity of 90 % RMT of the contralateral FDI/6 pulses (train duration 500 ms)	No rTMS (baseline), real rTMS (L DLPFC), real rTMS (R DLPFC), and sham rTMS (L DLPFC)/10 Hz-rTMS/An intensity of 90 % RMT of the contralateral FDI/6 pulses (train duration 500 ms)	rTMS of either L or R DLPFC increased the RT for spatially filtered living stimuli, but not of non-filtered living stimuli or of non-living objects.
tDCS					
Bogdanov et al. 2015 [4]	Sunk-cost effect (Cost of past expenses)	60 (F30)/Double-blind, sham-controlled, between-subject design.	R DLPFC (F4), a reference - CZ. Anodal, cathodal, or sham stimulation. A current of 1.075 μ A, leading to a current	R DLPFC (F4), a reference - CZ. Anodal, cathodal, or sham stimulation. A current of 1.075 μ A, leading to a current	Anodal tDCS significantly increased a sunk-cost effect, but cathodal or

Table 2 rTMS and tDCS studies in decision making (Continued)

			density of 0.043 mA/cm ² for the electrode over the DLPFC and 0.011 mA/cm ² for the reference electrode. The stimulation lasted for as long as the individual participant worked on the investment task but not longer than 30 min.	sham stimulation did not change it. Also, tDCS did not influence choices when there were no investments.
Boggio et al. 2010a [5]	risk-taking behavior	28 (M3, aged 50–85 years)/Single-center, doubled-blinded, randomized and sham-controlled trial	DLPFC/R anodal/L cathodal tDCS, L anodal/R cathodal tDCS, or sham stimulation. 2 mA. tDCS started 5 min before the task began and was delivered during the entire course of the risk task (10 min)	L anodal/R cathodal tDCS group caused more often high-risk prospects compared to sham or R anodal/L cathodal stimulation groups.
Boggio et al. 2010b [6]	addiction	25 marijuana users (M15)/Single-center, doubled-blinded, randomized, and sham-controlled trial	DLPFC/L anodal/R cathodal tDCS, R anodal/L cathodal tDCS, or sham stimulation. 2 mA. The tDCS started 5 min before the task began and was delivered during the entire course of the risk task (10 min)	Both L anodal/R cathodal tDCS of DLPFC and R anodal/L cathodal tDCS showed more risky tendencies in marijuana users. In marijuana users, R anodal/L cathodal tDCS decreased marijuana cravings.
Cheng & Lee 2015 [12]	risk-taking behavior	16/Single-blind, within-subjects design (3 experimental sessions on separate days)	DLPFC/left anodal/right cathodal, left cathodal/right anodal, or sham stimulation. 2 mA. Stimulation began 5 minutes before onset of experimental tasks and continued throughout completion of all tasks (within 19 minutes)	Left cathodal/right anodal tDCS over DLPFC decreased risk-taking under a context of haste. The reduction of risk-taking was larger in more impulsive individuals.
Fecteau et al. 2007a [18]	risk-taking behavior	36 (M11)/Single-blind design	DLPFC/R anodal/L cathodal tDCS, L anodal/R cathodal tDCS, or sham stimulation. 2 mA. tDCS started 5 min before the task began and was delivered during the entire course of the risk task (<10 min)	R anodal/L cathodal tDCS caused the safe prospect more often, compared to L anodal/R cathodal and sham stimulation
Fecteau et al. 2007b [19]	risk-taking behavior	35 (M9)/Single-blind design	DLPFC/R anodal/L cathodal tDCS, L anodal/R cathodal tDCS or sham stimulation. 2 mA. tDCS started 5 min before the task began and was delivered during the whole course of the BART (<15 min)	Groups receiving anodal tDCS over R or L DLPFC showed a risk-averse response.
Fecteau et al. 2014 [17]	addiction	12 smokers (M5)/Two five-day tDCS (active or sham) - A crossover, blind at four levels (group allocator, subjects, tDCS provider, outcome assessor), randomized, sham-controlled design (3 months separated the two tDCS regimens)	DLPFC/Active tDCS (R anodal/L cathodal tDCS) and sham stimulation. 2 mA for 30 min	Active tDCS decreased significantly the number of cigarettes smoked compared to sham stimulation and the effects maintained for 4 days.

Table 2 rTMS and tDCS studies in decision making (Continued)

Filmer et al. 2013 [22]	dual-task performance	18 (M3)/tDCS during three testing sessions on different days (The average time between sessions: 5 days)	L posterior lateral prefrontal cortex (pLPFC)/Anodal (9 min), cathodal (9 min), or sham (1 min 15 sec). Reference electrode - R supraorbital region/Current density: 0.029 mA/cm ² (current intensity = 0.7 mA).	Cathodal tDCS to L pLPFC reduced RT for the multitask session.
Fregni et al. 2008 [23]	food craving	23 (F21) - 21 completed the entire study (3 different sessions of treatment) (at 48-hour intervals)/Placebo-tDCS-controlled, randomized, double-blind, crossover study	DLPFC/L anode/R cathode tDCS, R anode/L cathode tDCS, and sham tDCS. 2 mA for 20 min.	Sham stimulation increased craving, but anode L/cathode R tDCS did not increase craving (anode L/ cathode R can suppress food craving).
Gorini et al. 2014 [26]	addiction	18 cocaine users (M10) & 18 non-abusers/ Single-blind, sham-controlled study	DLPFC. L anodal/R cathodal tDCS, R anodal/L cathodal tDCS, or sham stimulation (at least 48-hour intervals). 1.5 mA for 20 min.	BART: both cocaine users and non-abusers decreased risky behavior after both active tDCS. GDT: cocaine users increased safe behavior after R anodal stimulation and increased risk-taking behavior after L anodal stimulation, whereas control subjects increased safe behavior by only R anodal stimulation.
Hecht et al. 2010 [29]	probabilistic guessing	28 (M14)	DLPFC/R anodal/L cathodal group, L anodal/R cathodal group, or control group (no stimulation). 2 mA. tDCS started immediately before the prediction task began and was delivered during the whole course of the five-block experiment (~22 min)	No difference in strategy between the three groups, but participants in the left anodal/right cathodal group decreased RT when choosing the most frequent alternative.
Hecht et al. 2013 [30]	delay discounting	14 (F7)/Within-subject design (a minimum of 2 days (~47 h) interval between sessions)	DLPFC/R anodal/L cathodal tDCS, L anodal/R cathodal DLPFC tDCS, and sham stimulation 1.6 mA for 20 min	Anodal left/cathodal R DLPFC tDCS increased smaller immediate gains rather than larger-delayed options compared to sham stimulation.
Javadi et al. 2015 [34]	perceptual decision-making	12 (F6) - Exp1 & 45 (F26) - Exp2/Exp1 (n = 12) - only one stimulation condition (bilateral stimulation) & Exp2 (n = 45) - three stimulation conditions (bilateral, anodal unilateral, and cathodal unilateral stimulations)	Primary motor cortex (PMC) (C3 and C4)/Bilateral tDCS (L anodal PMC/R cathodal PMC, R anodal PMC/L cathodal PMC), Unilateral-anodal tDCS (L anodal PMC/R upper arm, R anodal PMC/L upper arm), Unilateral-cathodal tDCS (L cathodal PMC/R upper arm, R cathodal PMC/L upper arm)/1.5 mA for 10 min after the first phase and continued for another 5 min during the second phase.	Anodal tDCS over the PMC increased responses using the contralateral hand; whereas, cathodal tDCS over the PMC increased responses using the ipsilateral hand. In all tDCS conditions, RTs decreased when response shifted toward left hand

Table 2 rTMS and tDCS studies in decision making (Continued)

Kekic et al. 2014 [35]	food craving	F 20 with frequent food cravings/A double-blind sham-controlled within-subjects crossoverdesign	DLPFC/R anodal/L cathodal tDCS and sham tDCS. 2mA for 20 min.	and increased when response shifted away from the left hand. Active tDCS decreased craving for sweet foods, but not savory foods
Kuehne et al. 2015 [37]	moral judgment	F 20 with frequent food cravings/A double-blind sham-controlled within-subjects crossoverdesign	Anodal, cathodal, and sham stimulation - L DLPFC (reference electrode: R parietal cortex (P4). 10 min of tDCS before starting with the moral judgment task, with 2 mA and 5 seconds fade-in time. The stimulation continued and participants rated the personal moral dilemmas. The maximum stimulation time did not exceed 20min	Anodal stimulation - L DLPFC decreased individual appropriateness ratings and shifted toward non-utilitarian actions.
Mengarelli et al. 2015 [46]	choice modulation	48 (F28)	DLPFC, L cathodal tDCS, R cathodal tDCS (anode electrode - contralateral supraorbital area), or sham stimulation (over the same cortical areas, with the cathode electrode over the left and the right, respectively). 1 mA for 15 min	Cathodal tDCS - L DLPFC reduced choice-induced preference change.
Minati et al. 2012 [47]	risk-taking behavior	F47/Single-blind design	Three groups of female subjects (L anodal/R cathodal, R anodal/L cathodal, and sham tDCS)/DLPFC. 2 mA. Stimulation was enabled approximately 3 min before starting the task and disabled immediately upon completion (about 20.5 min)	R anodal/L cathodal tDCS significantly increased response confidence, independently of accept/reject response
Ouellet et al. 2015 [42]	decision-making and cognitive impulse control	45 (F29)/A single-blind, three-arm, randomized and sham-controlled study.	Orbitofrontal cortex (OFC)/L anodal left/R cathodal, R anodal left/L cathodal, or sham/1.5 mA for 30 min. Anodal and cathodal current densities of 0.04 mA/cm ² and 0.027 mA/cm ² , respectively.	Anodal tDCS over orbitofrontal cortex (OFC) regardless of laterality increased advantageous decision-making and cognitive impulse control, compared to sham tDCS.
Pripfl et al. 2013 [60]	addiction	18 smokers (F10) & 18 non-smokers (F15)/Within-subjects design (at least 1 week between sessions).	DLPFC/R anodal/L cathodal tDCS, L anodal/R cathodal tDCS, and sham stimulation. 0.45 mA (delivered over an electrode size of about 5 cm ²) for 15 min	In both the smoking and nonsmoking groups, risk taking was decreased in the "cold" task after the anodal left tDCS, whereas the opposite effect was seen in the "hot" task after anodal right tDCS.

Table 2 rTMS and tDCS studies in decision making (Continued)

Raja Beharelle et al. 2015 [61]	Exploration-exploitation trade-offs	79(F23)/Double-blind design	R Frontopolar Cortex (MNI peak: x = 27, y = 57, z = 6)/Anodal, cathodal, or sham tDCS/1 mA. The stimulation 3 min before subjects started the bandit task and continued throughout tasks	Cathodal stimulation increased choices of the highest rewards, but anodal stimulation influenced choices less by anticipated rewards, but rather by recent negative reward prediction errors
Smittenaar et al. 2014 [70]	model-based learning	22 (F11)/Within-subject, double-blind	R DLPFC/Anodal tDCS (cathodal electrode over the inion) and sham stimulation/2 mA for 25 min.	One stimuli was more strongly associated with the originally selected stimuli than the other. Active tDCS does not significantly affect model-based or model-free control during a behavioral task.
Woods et al. 2014 [79]	perception of space and time	16 (F10)/Three sessions on separate days (time range between sessions: 6–8 days).	Frontal - R anodal (F4)/L cathodal (F3), parietal - R anodal (CP4)/L cathodal (CP3) (1.5 mA for 20 min) or sham stimulations (F3/F4 or CP3/CP4 - counterbalanced across participants.	Parietal stimulation affected perception of spatial causality, while the frontal stimulation affected perception of both spatial and temporal causality.
Xu et al. 2013 [80]	addiction	24 smokers (F3)/Single-blind design	Anode tDCS - L DLPFC/cathode tDCS - R supra-orbital area (2 mA for 20 min) and sham stimulation	Anode tDCS - L DLPFC and cathode tDCS - R supra-orbital area decreased significantly negative affect.
Xue et al. 2012 [81]	maladaptive decision-making	18 (M9)	LPFC (the intersection of the F3–T3 line and the F7–C3 line)/Anodal tDCS - left lateral prefrontal cortex Control condition - Visual cortex (VC), Reference electrode - left cheek/1.5 mA for 10 min	Anodal tDCS - left LPFC increased the use of the gambler's fallacy strategy.
Ye et al. 2015a [82],	risk-taking behavior	60 (F36)	DLPFC/R anodal/L cathodal tDCS, L anodal/R cathodal tDCS or sham stimulation/2 mA for 15 min	Group receiving sham stimulation showed more conservative and safe options. Groups receiving either R anodal/L cathodal tDCS or L anodal/R cathodal tDCS did not show significant changes after tDCS.
Ye et al. 2015b [83]	risk-taking behavior	60 (F35)	R anodal/L cathodal DLPFC, L anodal/R cathodal DLPFC, or sham stimulation/2 mA for 15 min + another 3 min (second task)	R anodal/L cathodal tDCS induced more risky options in the gain frame and more safe options in the loss frame.

R right, L left, M male, F female

prefrontal cortex (MPFC) or the DLPFC using rTMS. When young healthy subjects performed delay-discounting tasks after 10 Hz-rTMS was applied to their MPFC or vertex stimulation (control condition), rTMS to the MPFC increased the preference toward delaying larger-sized rewards, while decreasing the choices for immediate small-size rewards (Cho et al. [13]). In another study, Sheffer et al. [69] showed that three sessions of HF rTMS (20Hz, 10 Hz, sham) over the left DLPFC decreased discounting of monetary gains and increased discounting of monetary losses in both smokers and nonsmokers, but had no effect on cigarette consumption in smokers. In Camus et al. [10] study, LF rTMS to the right DLPFC decreased values assigned to food stimuli. In their study, two control groups were added to the active rTMS group. The first control group received stimulation over the vertex, and the second control group received sham rTMS over the right DLPFC, using a placebo-stimulator. Compared to the two control groups, the group that received LF rTMS over the right DLPFC decreased their perceived values assigned to food stimuli. Because the MPFC has been reported to be related to reward encoding and outcome expectancies [48], HF rTMS to this region can shift reward decision-making from immediate to delayed rewards, which is implicated in goal-directed behaviors. HF rTMS to the left DLPFC can modulate monetary gains and losses; it has also been shown that LF rTMS to right DLPFC can decrease perceived values of food. These studies indicate that rTMS may be an effective tool for treating addiction.

When measuring rTMS's effects using the "dilemma" scenarios selected from a battery developed by Greene et al. [28], LF rTMS over the right DLPFC increased utilitarian responses during objective evaluation of moral dilemmas, compared to a sham group. For the results, the authors suggested that the right DLPFC stimulated by LF rTMS induced participants toward a rational cognitive control process, and integrated emotions caused by contextual information appraisal in moral judgments [72]. Buckholz et al. [9] studied blameworthiness and punishment decisions using LF rTMS over the DLPFC. LF rTMS over DLPFC lowered punishment ratings for culpable acts, but did not affect blameworthiness judgments. Tassy et al. and Buckholz et al.'s studies showed that rTMS can influence the judgement for moral problems.

On the other hand, rTMS can modulate cognitive functions. Inhibitory continuous theta burst stimulation (cTBS) to the angular gyrus (AG) affected decision-making tasks requiring visuospatial attention by disrupting the relationship between decision latencies and the probability of winning/losing [71]. In a study on the causal role of DLPFC in perceptual decision-making using a speeded perceptual categorization task (face-versus-car categorization task), LF rTMS applied to the left DLPFC decreased accuracy and increased RT compared to a sham condition [57]. In an object identification study using HF rTMS [77], when subjects performed object identification tasks consisting of spatially filtered living and non-living stimuli, HF rTMS of either the left or right DLPFC increased the RT for spatially filtered living stimuli, but not for non-filtered living stimuli or non-living objects. In a spatial working memory study [36], HF rTMS applied to both the right posterior parietal cortex (PPC) and the right DLPFC increased RT during the delay phase. The results showed that HF rTMS to the right DLPFC increased RT selectively during the decision phase, demonstrating the roles of the PPC and the DLPFC in the delay and decision phases related to spatial working memory. In a study on the lateral anterior temporal lobe (ATL) and the inferior parietal lobule

(IPL) in coding function (what for) and manipulation (how) of tools [33], LF rTMS to lateral ATL increased RT for the “function” judgments, whereas LF rTMS of IPL increased RT for the “manipulation” judgments. Gongora et al. [25] conducted a visuomotor task using LF rTMS and quantitative electroencephalography. After LF rTMS, compared to pre-LF rTMS, absolute beta power decreased in the Fp1 electrode and increased in the Fp2 electrode at rest before the task. During the task, the Fp2 electrode’s absolute beta power increased, F4 electrode’s absolute beta power decreased, and F7 electrode’s absolute beta power increased. After the task, at rest, F7 electrode’s absolute beta power decreased. The parietal regions (P3, Pz and P4)’s absolute beta power decreased during the visuomotor task compared to the rest conditions. The results showed interferences in parieto–frontal network through the changes of the absolute beta power by LF rTMS. These rTMS studies relevant to cognitive functions suggest that human cognitive abilities can be improved by brain stimulation.

In summary, in decision-making studies related to emotion, rTMS modulates delayed discounting [13, 69], food choice [10], moral judgment [72], and blameworthiness and punishment decisions [9]. In decision-making studies relevant to cognitive functions, rTMS affects visuospatial attention [71], perception [57], object identification [77], spatial working memory [36], function and manipulation tool knowledge [33], and visuomotor tasks [25].

tDCS

Recently, tDCS has been extensively used in decision-making studies (Table 2). In studies on risk-taking aversion using tDCS, Ye et al. [82] demonstrated that tDCS to the DLPFC could prevent wealth effect.¹ The group receiving sham stimulation showed more conservative and safer options. In contrast, groups receiving either right anodal/left cathodal or left anodal/right cathodal tDCS did not show significant changes after tDCS. The same research group [83] demonstrated that groups receiving the right anodal/left cathodal tDCS over DLPFC chose riskier options in the gain frame and safer options in the loss frame. These studies show that real tDCS to the DLPFC can reduce wealth effect and risk aversion, but the tendency differs depending on the gain and loss frame.

In Minati et al. [47]’s study, three groups (left anodal/right cathodal, right anodal/left cathodal, and sham tDCS to DLPFC) were compared while performing monetary gambles (potential win, loss, and outcome probability). The results showed that right anodal/left cathodal tDCS significantly increased response confidence, independently of accept/reject response, albeit tDCS did not affect task performance or risk propensity. tDCS also has shown different modulation effects in risk-taking behavior depending on age. For younger healthy subjects performing risk-taking tasks relevant to gambling, right anodal/left cathodal stimulation over the DLPFC caused the safe prospect to be chosen more frequently, compared to left anodal/right cathodal and sham stimulation [18]. In contrast, for older subjects (age: 50–85 years), left anodal/right cathodal stimulation caused high-risk prospects more often picked compared to sham or right anodal/left cathodal stimulation groups [5]. Cheng and Lee [12] studied risk-taking behavior using tDCS in young healthy subjects. Right anodal/left cathodal tDCS over DLPFC decreased risk-taking under a context of haste. The reduction of risk-taking was larger in more impulsive individuals.

When making a choice in a context of increasing risk, groups receiving anodal tDCS over the right or the left DLPFC (bilateral tDCS groups with cathodal tDCS to the

contralateral region of DLPFC) showed a risk-averse response. These groups made fewer pumps on the Balloon Analog Risk Task (BART) [39], which requires a choice in the context of increasing risk, than those with sham stimulation or unilateral DLPFC stimulation (anodal electrode over either the right or the left DLPFC with the cathodal electrode over the contralateral supraorbital region) [19].

Mengarelli et al. [46] performed an experiment relevant to choice modulation using tDCS. The authors showed that cathodal tDCS over the left DLPFC reduced choice-induced preference change when compared to sham stimulation while performing the Lieberman et al. [41]'s modified version of Brehm's free-choice paradigm. In a study on delay-discounting choices using tDCS [30], anodal left/cathodal right DLPFC tDCS increased smaller immediate gains rather than larger-delayed options compared to sham stimulation. A tDCS study on moral judgment [37] applied anodal, cathodal, and sham stimulation to the left DLPFC for the evaluation of moral personal dilemmas (Greene et al. [27]). As a result, subjects receiving anodal stimulation applied to the left DLPFC decreased individual appropriateness ratings and shifted toward non-utilitarian actions when compared to cathodal tDCS and sham stimulation. These studies show that tDCS can modulate the tendency of choice response in free-choice paradigms, delay discounting choices, and moral dilemmas, depending on the stimulated region of the DLPFC.

In a sunk-cost effect study using tDCS [4], anodal, cathodal, or sham stimulation was applied over the right DLPFC with a reference over CZ according to groups. Anodal stimulation significantly increased a sunk-cost effect, but cathodal or sham stimulation did not change it. Also, tDCS did not influence choices when there were no investments. The results indicate that the right DLPFC is involved with the sunk-cost effect. In an exploration (trying something new)-exploitation (sticking with a proven strategy) trade-offs study using tDCS [61], separated groups received anodal, cathodal, or sham tDCS over the right frontopolar cortex (FPC). Cathodal stimulation increased choices of the highest rewards, but anodal stimulation induced choices affected less by anticipated rewards and more by recent negative reward prediction errors, indicating that the right FPC is involved in controlling both exploration and exploitation. Ouellet et al. [42] studied decision-making and cognitive impulse control using tDCS. Anodal tDCS over orbitofrontal cortex (OFC) regardless of laterality increased advantageous decision-making and cognitive impulse control, compared to sham stimulation, indicating that controlling OFC by tDCS helps regulate impulsive behavior in psychiatric populations.

Regarding maladaptive decision-making as represented by the "gambler's fallacy," [81], anodal tDCS to the left lateral prefrontal cortex (LPFC) increased use of the gambler's fallacy strategy. This indicates that the left LPFC contributes to subprime decisions regarding random events by carrying out decisions based on a false world model (outcome dependency). Hecht et al. [29] performed a study regarding how decisions are made in a probabilistic-guessing task, which used tDCS to deliver stimulation to the DLPFC of one hemisphere while concurrently inhibiting the DLPFC of the opposite for each hemisphere of the participant's brain. Participants were randomly assigned to the right anodal/left cathodal group, left anodal/right cathodal group, or control group/no stimulation. Although there was no difference in strategy between the three groups, participants in the left anodal/right cathodal group decreased RT in choosing the most frequent alternative. The results may reflect that the left hemisphere plays an important role in probabilistic learning and reasoning.

Woods et al. [79] used both fMRI and tDCS to identify areas hypothesized to be associated with perception of space and time, and decision-making using animated video clips of billiard balls. Following the fMRI, tDCS was used to validate the hypothesized neural correlates found from the fMRI. Different tDCS manipulations during three different sessions were performed on different areas of the brain: frontal, parietal, or sham stimulations. Parietal stimulation affected perception of spatial causality, while frontal stimulation affected perception of both spatial and temporal causality, indicating that the parietal lobe is related to causal perception of space and the frontal lobe is related to more general functions such as decision-making. In addition, in order to investigate what role the left posterior lateral prefrontal cortex (pLPFC) played in dual-task performance, Filmer et al. [22] used tDCS during three testing sessions on different days while using different tDCS stimulations to the left pLPFC during each session: anodal, cathodal, or sham. Behavioral tasks included single and multi-tasking trials where participants had to respond to a tone, an image, or both. RT for the multitask session was significantly reduced by the cathodal stimulation to the left pLPFC. This finding supports the theory that the left pLPFC is a crucial location for multitasking in humans.

A recent study explored how anodal tDCS on the right DLPFC affects model-based reinforcement learning² vs. model-free learning techniques³ [70]. Smittenaar et al. [70] performed a within-subject double-blind study during two separate sessions in which participants were given either active or sham stimulation during a 2-alternative forced-choice task, followed by a choice of one of two of the second stage stimuli, in which one stimuli was more strongly associated with the originally selected stimuli than the other. Results showed that active tDCS does not significantly affect model-based or model-free control during a behavioral task.

For addiction studies using tDCS modulation, cigarette consumption was measured for two five-day tDCS applications (active or sham). In smokers, active tDCS (right anodal/left cathodal tDCS to the DLPFC) significantly decreased the number of cigarettes smoked compared to sham stimulation and the effects were maintained for 4 days [17]. Boggio et al. [6] applied tDCS to the DLPFC (left anodal/right cathodal tDCS, right anodal/left cathodal tDCS, or sham tDCS) to chronic marijuana users in their study. During the sham stimulation, they showed less risky decision-making more frequently than young healthy subjects had shown in their previous study [18]. Also, young healthy subjects receiving right anodal/left cathodal DLPFC tDCS showed less risky tendencies [18]; both left anodal/right cathodal and right anodal/left cathodal tDCS to DLPFC showed riskier tendencies in marijuana users. However, in marijuana users, right anodal/left cathodal tDCS of DLPFC decreased marijuana cravings significantly. In a study to compare cocaine users with non-abusers using tDCS [26], the subjects performed the BART and the Game of Dice Task (GDT) [7] immediately before and after each tDCS stimulation (a left anodal/right cathodal stimulation, a right anodal/left cathodal stimulation, and a sham stimulation at least 48-h intervals). For the BART, both cocaine users and non-abusers decreased risky behavior after both active tDCS. However, in the GDT, cocaine users increased their "safe" behavior after right DLPFC anodal stimulation and increased risk-taking behavior after left DLPFC anodal stimulation; however, control subjects increased safe behavior by only right DLPFC anodal stimulation. Pripfl et al. [60] investigated how anodal right/cathodal left DLPFC tDCS or anodal left/cathodal right DLPFC tDCS affect risk taking of smokers and nonsmokers by using the Columbia Card

Task (CCT) [21] to assess risky decision-making which uses “affect-charged” (Hot CCT) vs. deliberative (Cold CCT). In both the smoking and nonsmoking groups, risk taking was decreased in the “cold” task after the anodal left tDCS, whereas risk-taking was decreased in smokers but was increased in non-smokers in the “hot” task after anodal right tDCS. These results are important because they show that with an increased ability to control impulsivity, smokers made more cautious decisions, whereas hindering risk-aversion brain structures produced the opposite effect in nonsmokers. Also, in overnight abstinent smokers, anode tDCS to the left DLPFC and cathode tDCS to the right supra-orbital area significantly decreased negative affect, which positively correlated with the level of nicotine dependence but did not affect cigarette cravings and performance (RT and hit rate) on a visual attentional task [80]. Addiction modulation studies using tDCS suggest that tDCS can be effective tools for treating addictive behaviors in psychiatric populations.

In an appetite study using tDCS [23], anode left/cathode right tDCS of the DLPFC did not increase cravings, but sham stimulation did increase cravings, indicating that anode left/cathode right can suppress food cravings. In a study for women with frequent food cravings, anodal right/cathodal left tDCS decreased cravings for sweet foods, but not savory foods [35]. The study used temporal-discounting tasks to investigate impulsive-choice behavior of participants, showing that more reflective participants were more liable to tDCS effects inhibiting food cravings than more impulsive participants. However, there were no differences between real tDCS and sham tDCS in temporal-discounting tasks and actual food consumption. These studies indicate that food cravings in obesity populations may be controlled by tDCS.

In a perceptual decision-making study using tDCS [34], the brain region stimulated by tDCS was the primary motor cortex (PMC). Anodal tDCS over the PMC increased responses using the contralateral hand, whereas cathodal tDCS over the PMC increased responses using the ipsilateral hand. In all tDCS conditions, RTs decreased when response shifted toward the left hand and increased when response shifted away from the left hand. The results indicate that tDCS to the PMC can modulate motor responses and hand choice.

In summary, tDCS influences and modulates risk-taking behaviors [5, 12, 18, 19, 47, 82, 83], choice modulation [46], delayed discounting [30], maladaptive decision-making [81], probabilistic guessing [29], moral judgment [37], sunk-cost effect [4], exploration-exploitation trade-offs [61], decision-making and cognitive impulse control [42], perception of space and time [79], dual-task performance [22], model-based learning [70], addiction [6, 17, 26, 60, 80], food craving [23, 35], and perceptual decision-making [34].

Conclusions and future research direction

Recently, it has increasingly been reported that rTMS and tDCS can be applied to neuromodulation of various cognition and emotion functions. We reviewed emotion regulation and decision-making studies using rTMS and tDCS. Both rTMS and tDCS improve emotion regulation and decision-making abilities by modulating top-down regulation to the stimuli in experimental studies (Fig. 1). For rTMS, HF rTMS increases cortical excitability [2, 55], whereas LF rTMS inhibits cortical excitability [11]. The two stimulations induce neuronal plasticity [14, 40, 45, 74, 85, 86]. For tDCS, anodal stimulation increases the neuronal excitability and cathodal stimulation decreases the

neuronal excitability [50, 51]. Although tDCS's electrical fields tend to be more diffused and non-focal compared to rTMS [66], the two non-invasive tools are similar in improving or inhibiting the cognitive and emotional abilities. As mentioned above, emotion regulation and decision-making influence human behavior by top-down or bottom-up processing in the brain. rTMS and tDCS can modulate responses in behavioral tasks by influencing neuronal activation in the brain.

We reviewed the applications of rTMS and tDCS in emotion regulation and decision-making. Of rTMS and tDCS, tDCS takes advantages of emotion regulation and decision-making studies in perspective of simplicity of use and low expense. So far, tDCS has been extensively applied to decision-making tasks including moral judgment, risk-taking behaviors, choice modulation, delayed discounting, maladaptive decision-making, probabilistic guessing, perception of space and time, dual-task performance, model-based learning, addiction, food craving, sunk-cost effect, exploration-exploitation trade-offs, decision-making and cognitive impulse control, and perceptual decision-making. Comparatively, rTMS has been applied to delay discounting, food choice, moral judgment, visuospatial attention, perception, object identification, spatial working memory, function and manipulation tool knowledge, visuomotor task, and blameworthiness and punishment decisions. Thus far, tDCS studies for emotion regulation are more diverse than rTMS studies, such as arousal during emotion regulation, regulation of negative emotions in social exclusion, mathematics anxiety, emotional reactions to pain stimuli, negative affect for negative pictures, negative affect for negative stimuli, and momentary ruminative self-referent thoughts. On the other hand, rTMS has been applied to attentional aspects of emotion regulation, affective processing of emotional stimuli, autonomic reactions to affective pictures, and cerebellar stimulation. As such, tDCS has been used more extensively in a large variety of studies compared to rTMS, as shown in this review.

Reflecting on tDCS and rTMS studies in normal populations, more tDCS studies for patients with emotional and cognitive dysfunctions will be needed in the future. Although tDCS has been applied to the treatment of some psychiatric illnesses [84], there are few tDCS experiments that are applied either to clinical studies involving emotion dysregulation and abnormal decision-making such as suicidal ideations and attempts, or to severe problems in human relations and social adaptation. As opposed to rTMS's application to clinical patients, tDCS has not been used extensively with clinical populations. Considering the potential effects of tDCS, extensive broader application of tDCS to emotion dysregulation and abnormal decision-making in psychiatric patients is essential in the future. The possibility of tDCS relevance is strong in psychiatric diseases. Both rTMS and tDCS could provide many benefits for treatments with addiction and other self-control problems. In this review, we see that both rTMS and tDCS have many implications to benefit those who have emotion regulation deficiencies, and future studies should further investigate this.

Endnotes

¹Wealth effect means to be more conservative when expecting to get positive experiment benefits [24].

²learning based on inferences of the physical environment taken from observed data used to make future predictions.

³habitual responding which happens simply by saving information about outcomes and rewards from past encounters with the environment.

Abbreviations

rTMS, repetitive transcranial magnetic stimulation; tDCS, transcranial direct current stimulation; HF, High frequency; LF, Low frequency; PET, positron emission tomograph; DLPFC, dorsolateral prefrontal cortex; dACC, dorsal anterior cingulate cortex; TPJ, temporal parietal junction; SCR, skin conductance responses; rVLPFC, right ventrolateral prefrontal cortex; RT, reaction time; MPFC, medial prefrontal cortex; cTBS, continuous theta burst stimulation; AG, angular gyrus; PPC, posterior parietal cortex; ATL, anterior temporal lobe; IPL, inferior parietal lobule; BART, Balloon Analog Risk Task; FPC, frontopolar cortex; OFC, orbitofrontal cortex; LPFC, lateral prefrontal cortex; pLPFC, posterior lateral prefrontal cortex; CCT, Columbia Card Task; PMC, primary motor cortex

Acknowledgements

We appreciated Norah C. Hass for her comments and discussion on this paper.

Funding

This study was supported by the National Cancer Institute of the National Institutes of Health under Award Number R21CA184834 (PI: SLL). The content is solely the responsibility of the authors and does not necessarily represent the official views of the National Institutes of Health.

Availability of data and materials

Not applicable (All data came from previous studies listed in the references).

Authors' contributions

KMC and SLL conceived of the purpose for the review and its direction. KMC contributed to the development and organization of the manuscript. KMC wrote the first draft of the manuscript. SLL and DTS helped to revise the manuscript. All authors read and approved the final manuscript.

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Competing interests

The authors declare that they have no competing interests.

Consent for publication

Not applicable.

Ethics approval and consent to participate

Not applicable.

Received: 24 March 2016 Accepted: 2 June 2016

Published online: 10 June 2016

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