FACULTY OF PSYCHOLOGY
AND EDUCATIONAL SCIENCES

The role of mindfulness in the combined effects of tDCS and resonance breathing on stress

Word count: 7663

Vandenplas Nina

Student number: 01705924

Supervisor(s): Prof. Dr. De Raedt Rudi, Prof. Dr. Vanderhasselt Marie-Anne

A dissertation submitted to Ghent University in partial fulfilment of the requirements for the degree of Master of Science Clinical Psychology

Academic year: 2022 – 2023

GHENT
UNIVERSITY

Acknowledgements

First, I would like to thank my promotor, Prof. Dr. Rudi De Raedt, and my co-promotor Prof. Dr. Marie-Anne Vanderhasselt for giving me the opportunity to write this interesting thesis. Thank you Prof. Dr. De Raedt for taking your time to read this thesis and providing me with valuable feedback.

Secondly, I would like to thank my supervisor, Jens Allaert, for giving me the right guidance when I needed it. I appreciate you for taking the time to schedule meetings and giving me feedback.

Third, I would like to thank all the participants who helped us achieve the data that was needed to do research on this topic.

Lastly, I would like to thank all my fellow students, friends, family, and boyfriend who supported me throughout this whole process of writing a thesis. Thank you for listening to me when I needed it the most and especially thank you to everyone who reads this thesis.

Abstract

Literature has shown the effects of resonance breathing (slow paced breathing) and transcranial direct current stimulation (tDCS) as successful interventions for stress regulation. Moreover, mindfulness can also be a possible beneficial intervention to reduce stress. In this study the effects of these interventions and their interaction were investigated in relation to several physiological measurements (heart rate variability and blood pressure) and self-report measures (stress appraisal, negative affect, and positive soothing affect). In addition, this study also investigated if interindividual differences in the use of mindfulness could affect these effects. To assess this, participants were divided into 4 conditions that consisted of resonance versus control breathing combined with active versus sham tDCS. Next, participants were brought in a state of stress. The following hypotheses were made: first, we expected both active (versus sham) tDCS and resonance (versus control) breathing to be associated with lower negative affectivity, more positive soothing affect, lower stress appraisal, higher heart rate variability and lower blood pressure. Second, we expected the combination of active tDCS and resonance breathing to show the largest reductions in these stress indices. Finally, we expected these effects to be strongest amongst people with high natural tendencies towards mindfulness. Analysis of the interaction between breathing condition, tDCS and mindfulness showed that resonance breathing (compared to control breathing) presented the most promising results in reducing stress. Interindividual differences, such as trait mindfulness, has shown stronger results when combined with resonance breathing. For tDCS (separately or combined) no effects or even opposed effects were found in reducing stress.

Keywords: resonance breathing, heart rate variability, transcranial direct current stimulation (tDCS), mindfulness, stress appraisal, affect

Dutch Summary

Literatuur heeft aangetoond dat de effecten van resonantieademhaling en *transcranial direct current stimulation (tDCS)* succesvolle interventies zijn in het reguleren van stress. Daarnaast is mindfulness ook een mogelijke interventie om stress te reduceren. Deze studie ging de effecten van bovenstaande interventies na en bekeek hun interacties onderling aan de hand van verschillende fysiologische maten (hartslagvariabiliteit en bloeddruk) maar ook aan de hand van zelfrapportagematen (*stress appraisal*, negatief affect en een positief rustgevend affect). Als aanvulling ging deze studie na of interindividuele verschillen in de mate van mindfulness een rol spelen in de genoemde effecten. Participanten werden verdeeld in 4 condities die bestaan uit resonantieademhaling versus controle-ademhaling gecombineerd met *active tDCS* versus *sham tDCS*. Daarna werden participanten in een stresstoestand geplaatst. De volgende hypotheses werden gesteld: ten eerste verwachtten we dat zowel *active tDCS (*versus *sham tDCS)* en resonantieademhaling (versus controle-ademhaling) geassocieerd werden met lager negatief affect, meer positief rustgevend affect, lagere *stress appraisal*, hogere hartslagvariabiliteit en lagere bloeddruk. Ten tweede verwachtten we dat de combinatie van *active tDCS* en resonantieademhaling de grootste reductie in stress zouden teweegbrengen. Tot slot verwachtten we dat deze effecten het sterkst zouden zijn bij mensen met een natuurlijk grotere voeling met mindfulness. Analyse van de interacties tussen ademhaling, *tDCS* en mindfulness toonden aan dat resonantieademhaling (versus controle-ademhaling) resulteerde in een reductie van stress. Interindividuele verschillen zoals hoe mindfull iemand is, toonden sterkere resultaten wanneer ze gecombineerd werden met resonantieademhaling. *tDCS* toonde weinig effect of zelfs tegengestelde effecten in het reduceren van stress.

Trefwoorden: resonantieademhaling, hartslagvariabiliteit, transcranial direct current stimulation (tDCS), mindfulness, stress appraisal, affect

Table of Contents

Introduction

Stress is very common in our day-to-day life. Especially now, when we are challenged by a global pandemic. Our body produces a stress response to a threat coming from within ourselves or from the outside. It is a mechanism to protect ourselves from any potential harm that could hurt the body (Fink, 2010). This mechanism ensures a physical as well as a mental reaction to this trigger. For example, the idea of being infected with COVID-19 could trigger signs of stress but the actual virus will also initiate a stress response in the body (Fink, 2010). We can distinguish two types of stress: acute stress and chronic stress. Acute stress, such as for instance giving a presentation to a group, causes a peak in the experienced amount of stress. Chronic stress on the other hand, for example taking care of a sick family member for a while, causes lower levels of stress but persists longer. These levels of stress can be related to changes in the neuroendocrine system (Schindler, 1985). The changes occur in the hypothalamic-pituitary-adrenal axis (HPA) and the sympathetic nervous system (SNS) (Guilliams & Edwards, 2010). Chronically increased activity of the HPA axis can lead to major depression, anorexia nervosa, obsessive-compulsive disorder and panic disorder for example (Chrousos, 2009). Furthermore, decreased activity of the HPA axis can cause seasonal depression, chronic fatigue syndrome, adult post-traumatic stress disorder for instance (Chrousos, 2009). A meta-analysis of March-Llanes et al. (2017) found a relationship between stressful life events and psychopathology. They concluded that more stressful life events during adolescence can be a risk factor to develop internalizing and/or externalizing symptoms. These symptoms then increase the odds of developing psychiatric disorders later in life (March-Llanes et al., 2017). Stress can also influence blood pressure. Blood pressure consists of two values: systolic blood pressure and diastolic blood pressure. Systolic blood pressure measures the pressure on the vessels when the heart contracts. Diastolic blood pressure measures the pressure in the vessels when the heart relaxes (De Nederlands Hartstichting, 2022). Ideally, blood pressure (BP) varies round 120/80 mmHg. BP higher than 140/90 mmHg is called hypertension. Stress can cause elevated blood pressure levels which in its turn can cause hypertension (Pickering, 1995). Hypertension could be dangerous because it might increase the risk to develop cardiovascular diseases later on in life (Staessen et al., 2003). Given the crucial role of stress in the development of various mental health disorders, it is of importance to investigate methods to reduce stress in our lives (March-Llanes et al., 2017).

A possible way to reduce stress is to practice mindfulness. Mindfulness can be defined as “a moment-to-moment, non-judgmental awareness, cultivated by paying attention in a specific way, that is, in the present moment, and as non-reactively, as non-judgmentally, and as openheartedly as possible” (Kabat-Zinn, 2015). The mechanism behind mindfulness is based on recognizing automatic emotional patterns and focusing on physical reactions caused by these patterns. This change in thinking about life facilitates acceptance and looking at things another way without judging (van Vreeswijk et al., 2009). An important part of mindfulness is deep abdominal breathing also called diaphragmatic breathing (Arch & Craske, 2006). When breathing through the abdomen, the diaphragm is being engaged. With every inward breath, the diaphragm pulls down and the lungs fill more efficiently in comparison to thoracic breathing (Brownstone et al., 2021). An example of deep abdominal breathing is the mindful breathing exercise (MBE). This determines the ability to mindfully focus your attention on breathing during meditation (Burg & Wolf, 2012). Perciavalle et al. (2016) concluded that deep breathing techniques are effective to induce an improvement in mood and reduction of stress. Current treatment programs to use mindfulness are mindfulness-based stress reduction (MBSR) and mindfulness-based cognitive therapy (MBCT) (Burke, 2009). MBSR is a program that applies mindfulness meditation as an intervention associated with physical, psychosomatic, and psychiatric disorders (Grossman et al., 2004). The intervention presumes that greater awareness will provide better perception, reduce negative affect, and improve vitality and coping. A meta-analysis of Grossman et al. (2004) indicates that mindfulness training might enhance emotion regulation and lower discomfort in everyday life. This was consistently seen across a spectrum of standardized mental health measures including psychological dimensions of quality-of-life scales, depression, anxiety, coping style and other affective dimensions of disability. MBCT is a meditation program based on an integration of cognitive behavioral therapy for depression (Teasdale et al, 2002); the MBSR program is developed by Kabat-Zinn (1990). The original program prepares patients to develop skills that allow to disengage from habitual, automatic dysfunctional cognitive routines to reduce future risk of relapses and recurrences of major depression (Smith et al., 2007). MBCT could be useful for reducing residual depressive symptoms in patients with major depression and for reducing anxiety symptoms in patients with bipolar disorder in remission as well as in patients with some anxiety disorders (Hofmann & Gómez, 2017). Other mindfulness-based treatments are retreats and residential programs, brief mindfulness interventions, internet and smartphone mindfulness-based interventions (Hofmann & Gómez, 2017). A comprehensive meta-analysis concerning mindfulness-based therapy (MBT) concluded that MBT is moderately effective. MBT did not differ from traditional cognitive based therapy or behavioral therapies or pharmacological treatments. This meta-analysis also brings to conclusion that MBT is an effective treatment for a variety of psychological problems, and is especially effective for reducing anxiety, depression, and stress (Khoury et al., 2013). Whereas mindfulness is often used as a deliberate intervention to reduce stress, there are interindividual differences in the natural tendency to be in a mindful state. The study of Sala et al. (2019) quantified the relation between the trait mindfulness and health behaviors. They concluded that trait mindfulness shows a small correlation with several health behaviors (i.e., physical activity, healthy eating, sleep, alcohol use) (Sala et al., 2019). Furthermore, Shapiro et al. (2010) found that baseline trait mindfulness was a significant moderator of MBSR intervention effects. MBSR participants with higher levels of trait mindfulness showed a larger increase in mindfulness and subjective well-being over time, steeper declines in perceived stress, and higher levels of empathy and hope. The research above shows that mindfulness is a promising technique to reduce stress when interventions include a mindfulness component. However, interindividual differences in the natural tendency to be mindful could influence the outcome of mindfulness-based interventions. Current research suggests that people with a high tendency towards mindfulness might experience stronger therapeutic effects from interventions regarding mindfulness.

By performing mindfulness meditation exercises, individuals pay close attention to nuances in breathing. The beneficial breathing mechanism behind meditation exercises can be explained by heart rate variability (HRV) (Lehrer, 2014). There is a natural variability between heart beats that is called heart rate variability. It reflects the balance between the sympathetic nervous system and the parasympathetic nervous system. The sympathetic nervous system activates when a threat is perceived, for instance a snake. The body responds to this by elevating the heart rate and the HRV goes down. Simultaneously, the body also produces norepinephrine that activates the “fight-or-flight" system. The parasympathetic nervous system gives the body the opposite reaction and activates the “rest and digest” system. Acetylcholine slows down the heart rate and increases the HRV. The degree of variability in the HRV provides information about the functioning of the nervous control on the HRV and the heart’s ability to respond (Rajendra Acharya et al., 2006). Moreover, high HRV is associated with adaptive stress regulation, whereas low HRV is associated with maladaptive stress regulation (Kim et al., 2018). HRV can be changed by controlling the breathing frequency and activating the parasympathetic nervous system. This is known as resonance frequency breathing, which differs from individual to individual. We can influence an individual’s resonance frequency through heart rate variability biofeedback (HRVB). This technique consists of providing an individual with real-time feedback on heart rate and respiration changes while being instructed to breathe at low frequencies (Lehrer and Gevirtz, 2014). HRVB creates a maximized respiratory sinus arrhythmia (RSA). RSA is the heart pattern that appears when heart rate increases during inhalation and decreases during exhalation (Lehrer & Gevirtz, 2014). Respiratory linked variations in heart rate usually occur in the frequency range of 0.15-0.4 Hz (9-24 breaths/minute) in a healthy human adult. These are “high frequency” heart rate oscillations. “Low frequency” heart rate variability is within the range of 0.05-0.15 Hz (3-9 breaths/minute) (Berntson et al., 1997). To increase HRV researchers investigated different breathing patterns. They concluded that a breathing pattern of 5.5 breaths per minute (BPM) with an equal inhalation-to-exhalation ratio increased HRV significantly and boosted a feeling of relaxation compared with the baseline (Lin et al., 2014). Literature shows that HRVB and paced breathing at approximately six breaths per minute have positive effects on a variety of physical, behavioral, and cognitive conditions (Lehrer et al., 2020). A study of Steffen et al (2017) showed that a group of participants practicing resonance frequency breathing reported higher positive mood and had a significantly higher HRV ratio relative to a control group. The resonance frequency breathing group also showed lower systolic blood pressure when performing a stressful task. Monitoring HRV through HRVB could be a different method of decreasing stress. Recent research pointed out the association between HRV, stress and emotion regulation (Jentsch & Wolf, 2020). Reappraisal, a form of emotion regulation, caused significantly stronger increases in HRV during stress (Jentsch & Wolf, 2020). Therefore, controlled slow breathing (resonance breathing/ slow paced breathing) has a beneficial effect on stress regulation through changes in HRV and seems an easy to implement intervention (Lehrer & Gevirtz, 2014).

Another way to reduce stress is via noninvasive brain stimulation (NBS), such as transcranial direct current stimulation (tDCS) (Smits et al., 2020). This is a brain stimulation technique used for modulation of central nervous system excitability in humans. tDCS works by sending electric currents through the brain. The device includes two electrodes on each side of the individual’s scalp (Woods et al., 2016). Once these are placed, a current of around 1.0-2.0 milliampere is sent through the electrodes (Nitsche & Paulus, 2000). This mechanism triggers a subthreshold modulation of neuronal membrane potentials, which changes the cortical excitability (Nitsche et al., 2009). Smits et al. (2020) systematically reviewed and quantified the immediate effects of prefrontal non-invasive brain stimulation on emotional stress reactivity. Their findings give an indication that a single session of prefrontal NBS may be able to modulate negative emotional state in response to stress. The evidence for tDCS effects on subjective stress related emotions are sparse. However, the estimated effect size of single tDCS sessions in a non-clinical population is small. Smits et al. (2020) also discussed that there are differences between and within people regarding the effects of tDCS sessions. Moreover, Petrocchi et al. (2017) tested the effect of tDCS on vagally-mediated HRV and changes in momentary affect, and particularly in the so-called "soothing" positive affect. The authors found that vagally-mediated HRV and soothing positive affectivity can be enhanced after a single-session of tDCS. Factors that could influence the strength and direction of tDCS on prefrontal cortex sessions include for example: baseline neural activity (Antal et al., 2007; Fertonani et al., 2014), stress sensitivity (Peña-Gómez et al, 2011; Fitzgibbon et al., 2017), fatigue, task motivation and gender (Hurley and Machado, 2018). tDCS is most effective when simultaneously paired with a task (Baker et al., 2010). For instance, tDCS paired with speech therapy enhances speech motor recovery in stroke patients with aphasia (Baker et al., 2010). Also, Ahn et al. (2019) performed research pairing home-based tDCS with mindfulness-based meditation in older adults with knee osteoarthritis. They concluded that tDCS paired with mindfulness-based meditation tempered the pain, osteoarthritis-related clinical symptoms, and experimental pain sensitivity without adverse side effects in older adults with knee osteoarthritis. tDCS is an intervention used to reduce stress and influences HRV (a process involved in the mechanism behind breathing techniques) (Smits et al., 2020). Effect sizes of tDCS are relatively low and interindividual differences play an important role in the effectiveness of tDCS. These differences should be more investigated in the future (Smits et al. 2020). In addition, the effects of tDCS are stronger when it's combined with a task (e.g., paced breathing) (Baker et al., 2010). This gives perspective to investigate the combination of tDCS with resonance breathing/ paced breathing on stress regulation and how interindividual differences may influence outcomes.

To summarize, mindfulness can be a potential beneficial intervention to reduce stress (Khoury et al., 2013). A big part of mindfulness involves breathing techniques. Slow paced breathing increases vagally mediated HRV (Lehrer, 2014). The increased HRV has a positive impact on the body (Jentsch & Wolf, 2020). Another feasible way to reduce stress is to use non-invasive brains stimulation called tDCS (Smits et al., 2020). This intervention could also increase HRV but has more variability in the effectivity of it. The effectivity depends on interindividual differences and the presence of a task (e.g., paced breathing) (Smits et al., 2020)

(Baker et al., 2010). That's why the goal of current study is to combine slow paced breathing with tDCS assuming that both effects will amplify each other. This means that the effect of the two together will be stronger than both effects isolated. Given the importance of the role of interindividual effects when using tDCS, the trait mindfulness will be taken into consideration. Previous studies indicated that the trait mindfulness enhances the effect of a mindfulness-based intervention (Sala et al., 2019). Correspondent to these findings we expect that the effect of current study will be the strongest when people have a high trait mindfulness. To answer this research question, we will combine tDCS (active versus sham) with resonance breathing (resonance breathing versus control breathing) followed by a stress induction task (the calculus part of the Social Trier Stress Test) to induce stress. Stress regulation will be measured via self-reported measurements (affect and stress appraisal) as well as physiological measurements (HRV and blood pressure).

In summary, we expect both active (versus sham) tDCS and resonance (versus control) breathing to be associated with lower negative affectivity, positive soothing effect, lower stress appraisal, higher HRV and lower BP. Furthermore, we expect the combination of active tDCS and resonance breathing to show the largest reductions in these stress indices. Finally, we expect these effects to be strongest amongst people with high natural tendencies towards mindfulness.

Materials and Methods

Participants

The participants of this study include 161 individuals aged between 18 and 45. Selection criteria were a) normal or corrected to normal vision, b) no current psychiatric, neurological or respiratory disorders, c) no current use of psychiatric drugs, d) no personal or family history of epilepsy, e) no current neurosurgery, f) not pregnant, g) no metal or magnetic objects in or around the scalp. The study was executed with the approval of Ghent University's Medical Ethical Committee and in accordance with the Declaration of Helsinki. Participants provided informed consent at the start of the experiment and received 30 euros for participating. Participants were recruited from the general community via advertisements on online social media platforms (Facebook).

Materials

Transcranial direct current stimulation (tDCS)

tDCS was applied using a Neurosoft tDCS device. This device allows double-blinding of the tDCS conditions. tDCS was placed on the dorsolateral prefrontal cortex (DLPFC) of the participant for 20 minutes. The DLPFC was localized using the Beam localization method, the anode was placed over the left DLPFC and the cathode was placed over the right DLPFC (Mir-Moghtadaei et al., 2015). A current flow of 2 mA was sent through the electrodes during active tDCS. The electrodes were placed in a saline soaked sponge. Following the between subject design of the study, half of the participants received active tDCS and the other half received sham tDCS.

Breathing training

To train the participants the correct way of diaphragmatic breathing a geometric animation video was used. This animation expands and contracts while the participant inhales and exhales at the same rate as the animation. The rate corresponded to 5,5 breaths per minute. Participants practiced this way of breathing during a short training phase without tDCS. Once the participant has mastered the diaphragmatic breathing technique, participants will be shown the animation again accompanied with the brain stimulation during 20 minutes. Participants in the control group will be shown the same animation as the participants in the slow breathing group but at a different rate of breathing (5,5 BPM versus 15 BPM). Following the between subject design of the study, half of the participants followed the slow-paced breathing (5.5 BPM) and the other control group followed the 15 BPM breathing technique.

Stress induction

To induce stress, the Calculus Stress Induction task (part of The Trier Social Stress Test) was performed by the participants (Allen et al., 2017). Participants were asked to count backwards from 2083 in steps of 13. Once they made a mistake, participants heard a loud noise and had to start all over again. This task lasted for five minutes without the participant being aware of the duration of the task. To maximize stress, the participant was filmed during the task while the experimenter was seated in front of the participant. The camcorder's display was turned towards the participant. As a cover story, participants were informed that this is a communication task, and an external panel will analyze their performance during the task.

Psychophysiological measures

HRV. Cardiovascular reactivity was recorded at a 1000 Hz sample rate with the Biopac ECG100c amplifier, in conjunction with the Biopac MP150 (Biopac Systems Inc., Santa Barbara, CA). On the amplifier, the gain was set to 5000, mode set to normal, low pass filter set to 35 Hz and the high pass filter set to .05 Hz. Pre-gelled Ag/AgCL electrodes were placed according to the measurement of a lead II ECG. The data was collected in the Acqknowledge software on an external computer, together with event triggers that were sent by the MATLAB computer to the Biopac STP100c, via a USB interface. Using the PhysioData Toolbox 0.6.3 (Sjak-Shie, E. E. (2021). The signal was first filtered using a 1 Hz highpass filter and a 50 Hz lowpass filter, and R-peaks and interbeat intervals (IBIs) were subsequently automatically detected based on the following constraints: a) minimum R-peak of .5 mV, b) minimum IBI of .3 s, and c) maximum IBI of 1.5 s. Based on visual signal inspection, artifacts in the R-peaks and IBIs were then removed and interpolated if possible. Next, a continuous heart rate signal was computed via shape-persevering piecewise cubic interpolation at 100 Hz of the valid IBI data. Based on this signal, the following HRV indices were computed: the power in low frequency range of the power spectrum (LF), the power in high frequency range of the power spectrum (HF), the standard deviation of the NN intervals (SDNN) and the square root of the mean of the sum of the squares of difference between adjacent NN intervals (RMSSD). RMSSD was used for the analysis.

Blood pressure. The systolic (SBP) and diastolic (DBP) measurements of blood pressure were measured after each phase, by placing a validated oscillometric device (OMRON M6 Comfort; Asmar, 2011) on the right arm.

Self-report measures

Online survey. To make sure that there were comparable active and sham tDCS groups, an online survey assessing potential confounders was carried out before the experiment. This survey consisted of demographic, health, lifestyle, and psychological questions. Next, each variable was checked for significant differences between the 4 condition groups (i.e., active slow, active control, sham slow and sham control). When this check was performed, the participant was matched to a specific condition group.

Cognitive and Affective Mindfulness Scale-Revised CAMS-R. CAMS-R is a self-report measure of mindfulness. The scale consists of 12 items measuring: mindfulness, distress, well-being, emotion-regulation and problem-solving. The scale has an acceptable internal consistency and evidence of convergent and discriminant validity. (Feldman et al., 2006). This study shows a Cronbach's α of .79.

Affect. Participants were asked to rate their current levels of negative and positive affect using a total of 18 items. Negative affect was assessed by six emotions: upset, distressed, scared, angry, anxious, and sad. Activating (lively, energetic, active, enthusiastic, dynamic, excited) and soothing (relaxed, serene, content, calm, tranquil, peaceful) positive affect was assessed by the two subscales of the Activation and Safe/Content Affect Scale (Gilbert et al., 2008). This questionnaire will also be measured multiple times throughout the experimental procedure to assess any changes in affect. Negative affect and soothing positive affect were further analyzed in this paper.

Primary Appraisal Secondary Appraisal (PASA). PASA is a self-report measure that assesses cognitive appraisal processes in a stressful situation that contains of 16 items. This measurement consists of four scales: threat, challenge, self-concept of own abilities and control expectancy. Threat and challenge forms the first secondary scale, primary appraisal. Self-concept of own abilities and control expectancy forms the second secondary scale, secondary appraisal. The difference of primary and secondary appraisal forms the stress index which offers a global assessment of stress (Gaab, 2009). The stress index was further used to analyze cognitive appraisal processes in advance of the calculus stress task. Carpenter et al. (2016) concluded that PASA shows reasonable to good internal consistency. This study shows a Cronbach's α of .72.

Procedure

The study design used a full factorial (between-subjects) design based on the following group conditions: breathing (slow vs control) x transcranial Direct Current Stimulation (tDCS) (sham vs active). Next, participants filled in an online survey. Based on this survey, participants were assigned to one of four conditions. Later, on the day of the experiment, electrocardiogram blood pressure recording devices were attached to the participant. Participants then sat quietly for a period of five minutes during which a physiological baseline recording is collected ((HRV), heart rate and blood pressure). These physiological measures were assessed throughout the whole experiment, during all the phases described below. After five minutes of physiological baseline recording, two short questionnaires were assessed (AF and PTQ-S). AF and PTQ-S were administrated throughout the experiment, to index changes in cognitions and mood. Later participants were familiarized with the structure of the experiment. Participants in the experimental (resonance) breathing condition were instructed in the diaphragmatic (abdominal) breathing technique. Afterwards participants again completed two short questionnaires (AF and PTQ). tDCS was applied and turned on for 20 minutes, during which the participant performs their respective breathing task (resonance frequency breathing or control frequency breathing). Afterwards participants again completed two short questionnaires (AF, PTQ). Next, participants performed the calculus stress induction task. After introducing the task, participants reported primary and secondary stress appraisal (PASA). Afterwards participants again completed two short questionnaires (AF, PTQ). At the end of the session, participants were debriefed about the purpose of the study.

Data Analytic Plan

Analysis of the dependent variables (HRV, BP, PASA and AFFECT) and independent variables (breathing condition, tDCS group, phase and mindfulness) were performed in R 4.0.2 (R Core Team, 2013). For HRV, BP and PASA linear mixed models (LMMs) were used and fitted via the 'lmer' function of the 'lme4' R package (Bates et al., 2014). Given the absence of repeated within-subject measurements of the PASA, a linear model was used to analyse PASA. The p-value cut-off was set to $p < .05$ and p-values for the fixed effects were estimated with the 'lmerTest' R package, using the Satterthwaite approximations to degrees of freedom (Kuznetsova et al., 2017). Mindfulness was standardised before the model was fitted. For interaction effects where mindfulness was implied, the following follow-up tests were carried out at different levels mindfulness, by computing the EMMs at two values ($M - 1$ *SD* [low], $\mathrm{M} + 1$ *SD* [high]) of mindfulness. The analysis-of-variance tables were computed via the 'anova' R function, with the sum of squares estimated using the type III approach (Fox et al., 2012). Follow-up tests were completed via pairwise comparisons of the estimated marginal means (EMMs) computed via the 'emmeans' function of the 'emmeans' R package (Lenth, 2018). When relevant, the p-values from follow-up tests were adjusted for multiple comparisons using the false discovery rate correction (Benjamini & Hochberg, 1995). Before the data was analysed a visual inspection was performed to exclude any invalid data. If needed, outliers were removed by the double Median Absolute Deviation function (MAD; Leys et al., 2013). By performing this function to the data, 15% of the HRV data was rejected.

First, to check whether HRV results were influenced by either breathing (resonance vs control breathing), tDCS (active vs sham), phase (habituation, breathing and calculus) conditions or mindfulness. A linear mixed model was used to fit RMSSD as dependent variable. Breathing (resonance vs control breathing), tDCS (active vs sham), phase (habituation, breathing and calculus) and mindfulness were used as fixed, independent variables. Subject was entered as a random intercept.

Second, to check whether SBP/ DBP results were influenced by either breathing (resonance vs control breathing), tDCS (active vs sham), phase (habituation, breathing and calculus) conditions or mindfulness. A linear mixed model was used to fit SBP as dependent variable. Breathing (resonance vs control breathing), tDCS (active vs sham), phase (habituation, breathing and calculus) and mindfulness were used as fixed, independent variables. Subject was entered as a random intercept.

Third, to check whether PASA results (stress-index) were influenced by either breathing (resonance vs control breathing), tDCS (active vs sham) or mindfulness. A linear model was used to fit PASA (stress-index) as dependent variable. Breathing (resonance vs control breathing), tDCS (active vs sham) and mindfulness were used as independent variables.

Finally, to check whether negative/ positive soothing affect results were influenced by either breathing (resonance vs control breathing), tDCS (active vs sham), phase (habituation, breathing and calculus) conditions or mindfulness. A linear mixed model was used to fit negative affect as dependent variable. Breathing (resonance vs control breathing), tDCS (active vs sham), phase (habituation, breathing and calculus) and mindfulness were used as fixed, independent variables. Subject was entered as a random intercept.

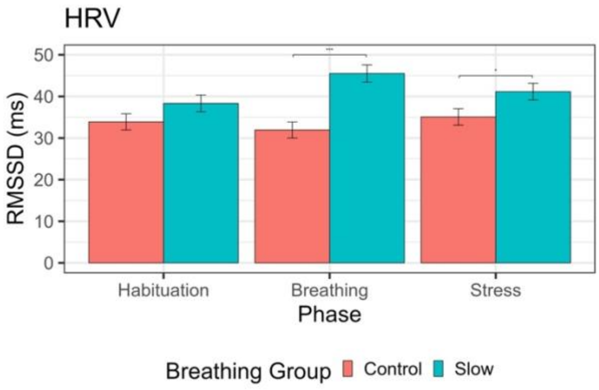
Results

Effects of breathing condition, tDCS group, mindfulness, and phase of the experiment on HRV

The LMM for HRV showed a significant main effect of *breathing condition*, F (1,121.79) = 12.39, $p < .001$, in the presence of a significant higher-order *breathing condition* x *phase* interaction effect, *F* (2,228.17) = 5.79, *p* = .004. Follow-up pairwise comparisons of the EMMs on the interaction effect proved that during the breathing phase in the experiment participants performing slow breathing exhibited a higher HRV in comparison to participants performing controlled breathing, *b* = -13.58, SE = 2.83, *t* = -4.79, *p* < .0001. During the calculus stress task phase participants performing slow breathing demonstrated a higher HRV in comparison to participants performing controlled breathing, *b* = -6.07, SE = 2.82, *t* = -2.15, *p* < .03. During the habituation phase there was no difference found between both groups, *b* = -4.43, SE = 2.79, *t* = -1.59, *p* = 0.11 (see figure 1). All other effects in the model were not significant with *p*-values greater than 0.08 and a *F*-values smaller than 2.60 (df = 2,238.49).

Figure 1

Effect of breathing condition and phase on HRV



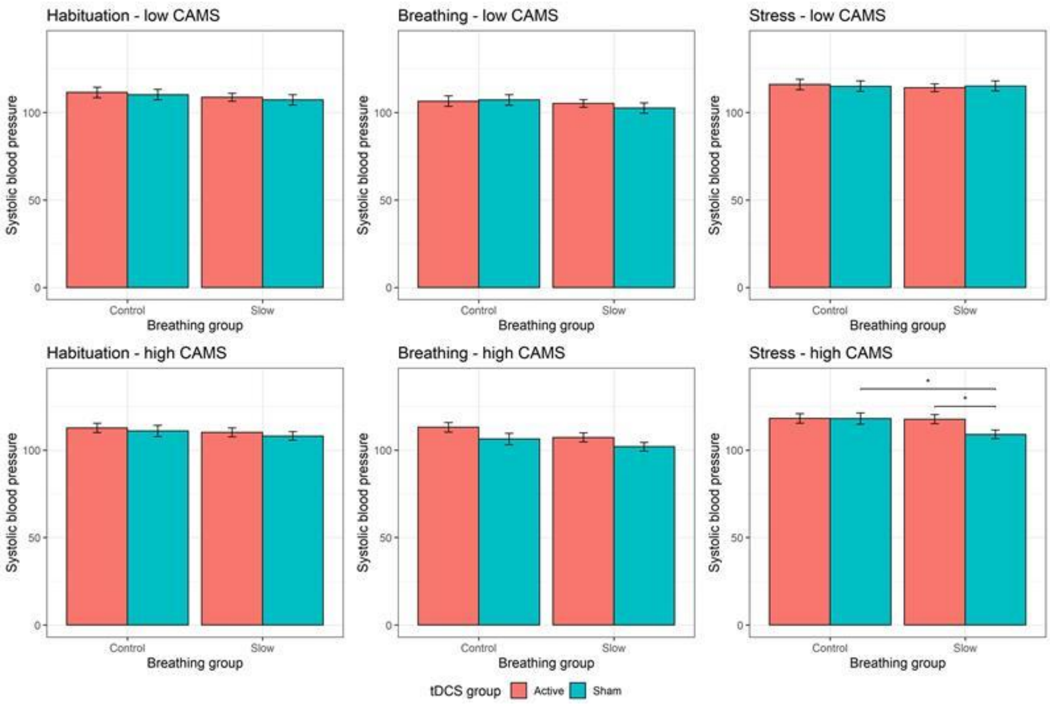
Note. * ≤ .05, ** ≤.01, *** ≤ .001

Effects of breathing condition, tDCS group, mindfulness, and phase of the experiment on systolic blood pressure (SBP)

The LMM for SBP showed a significant main effect of *phase*, *F* (2,314) = 12.39, *p* < .001, in the presence of a significant higher order *tDCS* x *breathing condition* x *phase x mindfulness* interaction effect, *F* (2,314) = 82.13, *p* < .0001. Follow-up pairwise comparisons of the EMMs on the interaction effect demonstrated that during the stress phase participants performing slow breathing, who received sham tDCS, who also scored high on mindfulness, exhibited a lower SBP in comparison to control breathing, *b* = 9.09, SE = 4.08, *t* = 2.23, *p* = 0.027. Furthermore, during the stress phase, participants performing slow breathing and receiving sham tDCS, who also scored high on mindfulness, exhibited a higher SBP in comparison to active tDCS, *b* = 8.70, *SE* = 3.58, *t* = 2.43, *p* = 0.016 (see figure 2). All other effects in the model were not significant with *p*-values greater than 0.06 and a *F*-values smaller than 3.55 (df = 1,157). To conclude, the reduction of SBP is associated with slow paced breathing (versus control) breathing was only presented in participants who scored high on the trait mindfulness during moments of stress receiving sham tDCS. Moreover, an increase of SBP was associated with active tDCS (versus sham tDCS) within participants who scored high on the trait mindfulness during moments of stress when performing slow paced breathing.

Figure 2

Effects of breathing condition, tDCS group, mindfulness, and phase on systolic blood pressure



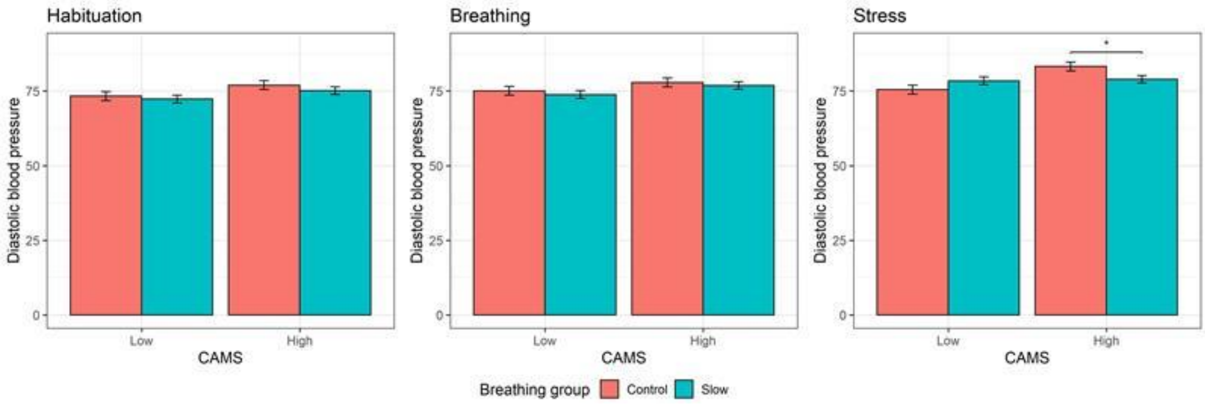
Note. * ≤ .05, ** ≤.01, *** ≤ .001

Effects of breathing condition, tDCS group, mindfulness, and phase on diastolic blood pressure (DBP)

The LMM for DBP demonstrated significant main effects of *phase, F* (2,314) = 24.93, *p* < .001 and *mindfulness*, *F* (1,157) = 8.36, *p* = .0044 in the presence of significant higher-order *tDCS x breathing condition* effect, *F* (1,157) = 5.17, *p* = .02. Follow-up pairwise comparisons of the EMMs on the *tDCS x breathing condition* interaction demonstrated that participants receiving active tDCS and performing slow paced breathing showed a lower DBP in comparison to participants receiving sham tDCS, *b* = 3.19, *SE* = 1.56, *t* = 2.05, *p* = 0.042 (see figure 4). Furthermore, participants receiving sham tDCS whilst performing slow paced breathing, exhibited a lower DBP in comparison to controlled breathing, b = 3.56, SE = 1.53, t = 2.32, p = 0.022 (see figure 4). For the *breathing condition x phase x mindfulness* interaction effects, F (2,314) = 3.98, p = 0.02, follow-up pairwise comparisons of the EMMs demonstrated that during the calculus stress task phase participants performing slow paced breathing who scored high on mindfulness showed a lower DBP in comparison to controlled breathing, b = 4.30, SE = 1.95, t = 2.20, p = 0.03 (see figure 3). All other effects in the model were not significant with p-values greater than .22 and a F-values smaller than 1.53 (df = 2,314). In conclusion, the reduction of DBP was associated with slow paced breathing (versus control) breathing when receiving sham tDCS. And the reduction of DBP was associated with active tDCS (versus sham tDCS) when performing slow paced breathing. Moreover, the reduction of DBP was associated with slow paced breathing (versus control) breathing was only presented in participants who scored high on the trait mindfulness during moments of stress independent of tDCS group.

Figure 3

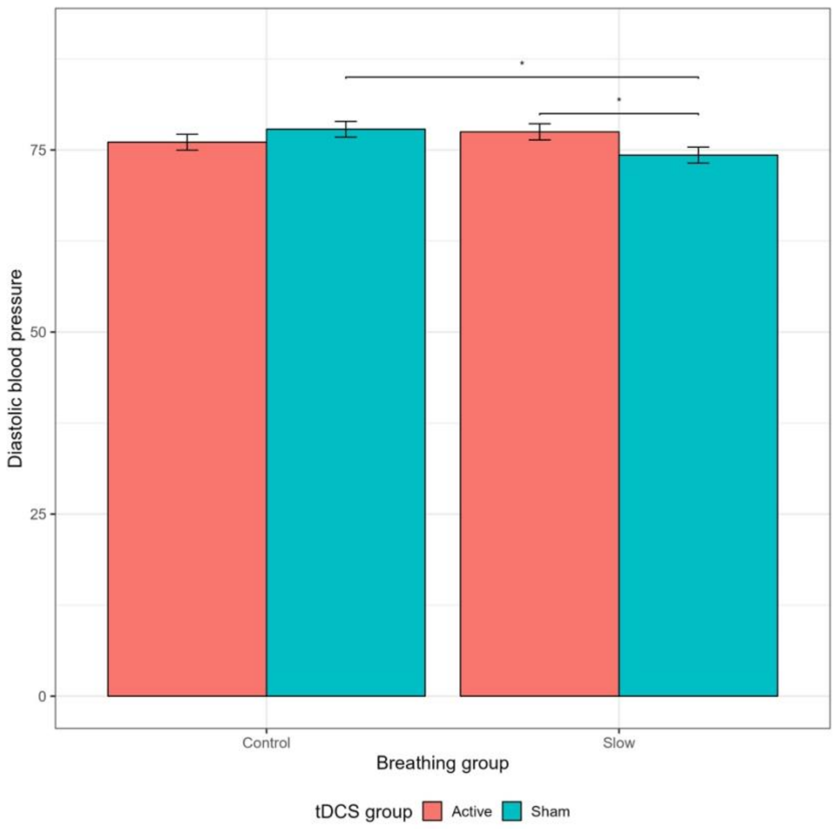
Effects of breathing condition, mindfulness, and phase on diastolic blood pressure



Note. * ≤ .05, ** ≤.01, *** ≤ .001

Figure 4

Effects of breathing condition and tDCS group on diastolic blood pressure



Note. * ≤ .05, ** ≤.01, *** ≤ .001

Effects of breathing condition, tDCS group, mindfulness, and phase on PASA

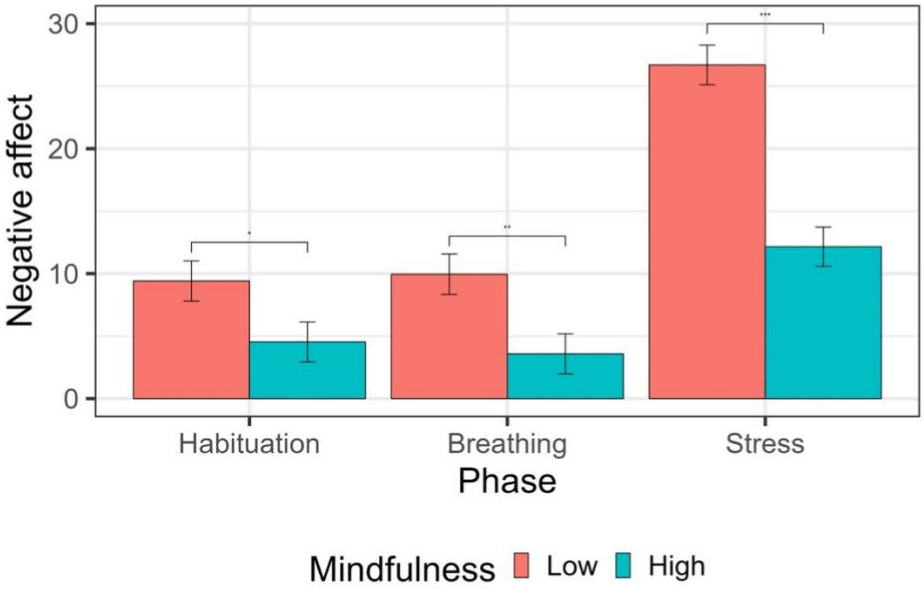
To analyse the data concerning PASA, we chose to work with the stress index. The linear model for PASA demonstrated no significant effects with *p*-values greater than .27 and a *F*-values smaller than 1.24.

Effects of breathing condition, tDCS group, mindfulness, and phase on negative affect

The LMM for negative affect demonstrated significant main effects of phase, *F* (2, 303.08) = 71.84, *p* < .001 and mindfulness, *F* (1,154.66) = 23.17, p < .001 in the presence of a significant higher-order *phase* x *mindfulness* interaction effect, *F* (2,304.87) = 7.68, *p* < .001. All other effects in the model were not significant with *p*-values greater than .18 and a *F*-values smaller than 1.9 (df = 1,152.81). Follow-up comparisons of the EMMs between high and low levels of trait mindfulness at each phase showed that individuals scoring high (compared to low) trait mindfulness displayed less negative affectivity during the habituation, *b* = -2.44, *SE* = 1.19, *t* = -2.05, *p* = 0.04, breathing, *b* = -3.19, *SE* = 1.19, *t* = -2.67, *p* = 0.08, and stress, *b* = -2.27, *SE* = 1.16, *t* = -6,28, *p* <.001 phase. Importantly, this difference in negative affect between high and low levels of trait mindfulness was more strongly present during the stress as compared to the breathing, *b* = 4.09, *SE* = 1.35, *t* = 3.07, *p* = .00, and habituation phase, *b* = 4.83, *SE* = 1.33, *t* = 3.63, *p* = .00 (see figure 5).

Figure 5

Effects of breathing condition, mindfulness, and phase on negative affect



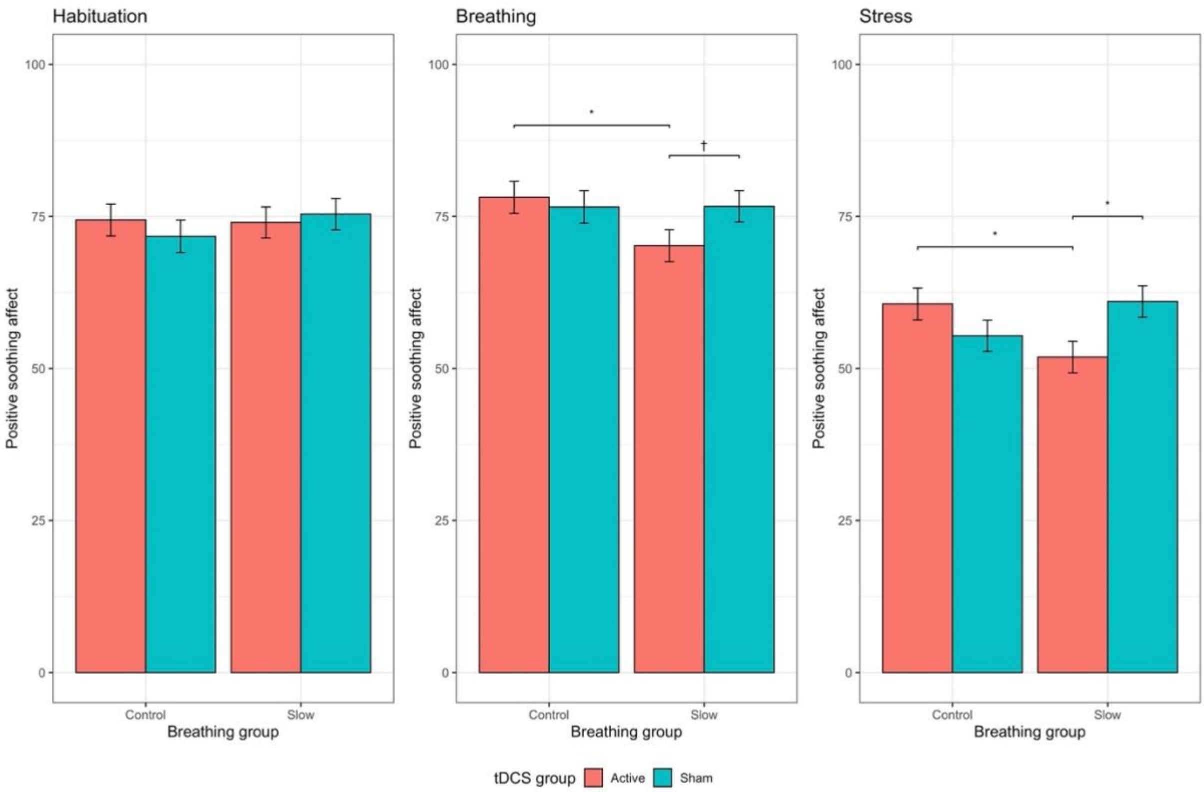
Note. * ≤ .05, ** ≤.01, *** ≤ .001

Effects of breathing condition, tDCS group, mindfulness, and phase on positive soothing affect

The LMM for positive soothing affect demonstrated significant main effects of *phase*, *F* (2, 303.81) = 94.62, *p* < .001 and *mindfulness*, *F* (1, 155.42) = 36.65, *p* < .001 in the presence of significant higher-order interaction effect, *breathing condition* x *tDCS F* (1, 153.56) = 4.96, p = .03. Follow-up pairwise comparisons of the EMMs on the interaction effect *breathing condition* x *tDCS* demonstrated that there is only a significant effect of breathing condition during active tDCS (versus sham tDCS), *b* = 5.70, *SE* = 2.80, *t* = 2.03, *p* = .04. Next, follow-up pairwise comparisons of the EMMs on the interaction effect *tDCS* x *breathing group* demonstrated that active tDCS whilst breathing in the slow condition (versus control condition) is associated with lower positive soothing effect. To conclude, there is only an effect of breathing when participants receive active tDCS. This effect demonstrated that slow breathing is associated with lower levels of positive soothing affect. Also, when participants perform slow breathing, active tDCS is associated with lower levels of positive soothing affect. These effects are complementary to each other (see figure 6). The next significant higher-order interaction effect regards tDCS x *mindfulness* F (1, 155.42) = 4.81, p < .03. Follow-up pairwise comparisons of the EMMs on the interaction effect *tDCS group* x *mindfulness* demonstrated that when participants receive active tDCS, participants who score high on the trait mindfulness experience more positive soothing affect compared to participants who score low on the trait mindfulness b = 4.77, SE = 2.18, t = 2.19, p = .03. The last significant higher-order interaction effect regards *phase* x *mindfulness*, F (2, 305.60) = 5.63, p < .004. Follow-up comparisons of the EMMs between high and low levels of trait mindfulness at each phase showed that individuals scoring high (compared to low) trait mindfulness displayed more positive soothing affectivity during the stress, b = 9.46, SE = 1.41, t = 6.72, p <.001, breathing, b = 6.19, SE = 1.45, t = 4.28, p <.001, and habituation, b = 4.10, SE = 1.45, t = 2.83, p = .00 phase. Importantly, this difference in positive soothing affect between high and low levels of trait mindfulness was more strongly present during the stress as compared to the habituation phase, b = -5.37, SE = 1.61, t = -3.24, p = .03 (see figure 7). All other effects in the model were not significant with p-values greater than .07 and a F-values smaller than 3.43 (df = 1, 155.42).

Figure 6

Effects of breathing condition, tDCS group and phase on positive soothing affect



Note. * ≤ .05, ** ≤.01, *** ≤ .001

Figure 7

Effects of mindfulness and phase on positive soothing affect

Note. * ≤ .05, ** ≤.01, *** ≤ .001

Discussion

The aim of the present study was to discover the effects of prefrontal tDCS combined with resonance breathing on HRV, BP, stress appraisal, affect and how interindividual differences in the use of mindfulness affects these. We expected these effects to be strongest amongst people with high natural tendencies towards mindfulness.

First, effects of breathing condition, tDCS group, mindfulness, and phase of the experiment on HRV were analysed. During moments of stress, slow breathing increased HRV in comparison to controlled breathing. These results are in line with the research done by Lehrer and Gevirtz (2014) and Lin et al. (2014) that an individual's HRV can be changed by controlling the breathing frequency. However, these results partially corroborate the hypothesis that both active tDCS and resonance breathing are associated with higher HRV. The effect, as seen in research of Baker et al. (2010), that the effects of tDCS are stronger when combined with a task are not seen in this study. This could be due to the small effect sizes and interindividual differences within participants using tDCS (Smits et al., 2020). Moreover, a recent study of Jonker et al. (2021) concluded that performing anodal tDCS did not affect cortical excitability which corroborates to other recent null findings of tDCS (Horvath et al., 2016). Further investigation will be needed to understand the small effect sizes (or even null findings) of tDCS.

Second, effects of breathing condition, tDCS group, mindfulness, and phase of the experiment on systolic and diastolic blood pressure were analysed. During moments of stress, slow breathing combined with sham tDCS in people who have a high tendency towards mindfulness was associated with lower systolic blood pressure. Furthermore, during the stress phase, participants performing slow breathing and receiving sham tDCS, who also scored high on mindfulness, exhibited a higher SBP in comparison to active tDCS. But when looking at diastolic blood pressure during moments of stress, no interaction with tDCS was found, only slow breathing and a high tendency towards mindfulness were associated with lower diastolic blood pressure. These findings were counter to our expectations, as we expected that the interaction of active tDCS with slow breathing in people who have a higher tendency towards mindfulness would decrease blood pressure. A potential explanation for the observed effect could be that participants experienced physical discomfort due to active tDCS. As tDCS is known as a safe and tolerable method of non-invasive brain stimulation, perceived side-effects such as tingling, itching, burning, or pain are commonly reported by participants (Dundas et al., 2007). A study of Kessler et al. (2012) discussed that although subjects are unable to explicitly discriminate between active and sham stimulation, the implicit experience of the two conditions was different. This means that the experience of active and sham stimulation is not the same among some individuals.

Third, effects of breathing condition, tDCS group, mindfulness, and phase of the experiment on stress appraisal (PASA) were analysed. There were no significant effects found during this study. These finding are not in line with a previous study done by Weinstein et al. (2009). They discussed that individuals with a higher tendency towards mindfulness were likely to view challenging situations as less stressful or threatening. A possible explanation could be that this study focused on the trait mindfulness without looking at someone's state of mindfulness. Goilean et al. (2021) clarified the relationship between trait mindfulness and state mindfulness. Trait mindfulness refers to "the innate capacity of paying and maintaining attention to present-moment experiences with an open and non-judgmental attitude" (Brown & Ryan, 2003). Whereas state mindfulness refers to "the extent to which an individual is currently aware of and paying attention to stimuli occurring in the present" (Brown & Ryan, 2003). The study of Tang et al. (2016) suggested the importance of investigating mindfulness during different points of a study to differentiate between dispositional mindfulness (known as the trait mindfulness) and the effective practice of mindfulness (state mindfulness) (Tang et al., 2015). More research will be needed to investigate the relationship between someone's state mindfulness in relation to stress reduction. It could also be interesting to investigate the relationship between mindfulness and tDCS in a more ecologically valid setting. People who are more mindful often create a lifestyle or habits to incorporate mindfulness practices (Mantzios & Giannou, 2019). Future research could incorporate ecological momentary assessment (EMA) for example. EMA is “a collection of methods aimed at measuring people’s behaviours (e.g., smoking, physical activity) and experiences (e.g., thoughts, feelings, beliefs, urges, pain, and cardiac activity) at the moment they occur (or shortly thereafter), in their own natural setting, using technologies such as personal digital assistants, smartphones, or wearable biosensors” (Enkema et al., 2020).

Last, effects of breathing condition, tDCS group, mindfulness, and phase of the experiment on negative and positive soothing affect were analysed. Results showed that individuals scoring high (compared to low) trait mindfulness displayed less negative affectivity during all phases of the experiment, but this effect showed the strongest results during moments of stress. These findings are in line with the meta-analysis regarding mindfulness training (Grossman et al., 2004). This meta-analysis concluded that mindfulness might enhance emotion regulation as well as lower discomfort in everyday life (such as negative affect). MBSR specifically enhances ways of coping with stress and disability. However, the combination of tDCS (sham nor active) and breathing condition on phase did not show a significant effect on negative affect. The study done by Morgan et al. (2014) also concluded that tDCS did not influence positive or negative affect. A possible explanation why breathing condition showed no significant effect on negative affect could be due to the number of breathing sessions. Ma et al. (2017) conducted a study where participants received intensive training of diaphragmatic breathing for 20 sessions, implemented over 8 weeks. Their findings suggested that diaphragmatic breathing showed a significant decrease in negative affect after intervention, compared to baseline. Looking at positive soothing affect, participants who received active tDCS whilst breathing in the slow condition, demonstrated a lower positive soothing affect during the stress phase. Also, when participants performed slow breathing, active tDCS decreased the experience of positive soothing affect. These results are opposed to the hypothesis that active tDCS, resonance breathing and a high tendency towards mindfulness demonstrate a higher positive soothing affect. As discussed before, further research will be needed to understand the variability of the effectiveness of tDCS. Finally, participants who score high on the trait mindfulness experience more positive soothing affect during the stress phase (in comparison to the other phases). This effect has also been seen by Petrocchi et al. (2017), as soothing positive affect can be enhanced by active tDCS.

As for clinical implications, as seen in research, stressful life events can be a risk factor to develop internalizing and/ or externalizing symptoms which can cause the increase of the odds of developing psychiatric disorders later in life (March-Llanes et al., 2017, Chrousos 2009). This shows the importance to investigate ways of reducing stress in our lives (March-Llanes et al., 2017). Results of this study confirmed that participants with a high natural tendency towards mindfulness performing resonance breathing during moments of stress, experience lower levels of stress. Mindfulness-based interventions are safe, convenient, cost-effective, and can be recommended for major depressive disorder, PTSD, bipolar disorder, and some anxiety disorders (Khusid & Vythilingam, 2016, Hofmann & Gomez, 2017). Performing resonance breathing is an easy to implement intervention in most individuals as it can be achieved with simple practice (Lehrer & Gevirtz, 2014, Russo et al., 2017). Russo et al. (2017) discussed that they haven't found any documented adverse effects of breathing at a pattern of 6-10 BPM. For tDCS (separately or combined) no effects or even opposed effects were found in reducing stress during this study. Vanderhasselt and Ottaviani (2022) proposed that resonance breathing, and neuromodulation are both evidence-based methods to increase vagal nerve inhibitory control and increase stress resilience. As resonance breathing is a bottom-up approach and neuromodulation a top-down approach, both can be used alone or in combination. However, effect sizes of tDCS are relatively low and interindividual differences play a role in its effectivess (Smits et al., 2020). Moreover, tDCS has its limitations (such as side-effects) and costs more compared to performing resonance breathing.

Strengths and limitations

A strength of this study is the combination of physiological measurements and self-report measures. By combining both types of measurements, limitations of both measurements could be minimalized. One of the limitations of this study is that the study employed healthy participants as our target population. Future studies should investigate if these relationships hold in people with clinical diagnoses. Another possible limitation of this study is the between-subject design. As discussed before, individual differences play an important role in the effectiveness of tDCS. Although this study made sure that potential confounders were carried out, it is impossible to check for all possible confounders (Bhandari, 2022). Another limitation is that participants only practiced the diaphragmatic (abdominal) breathing technique once during the experiment. This might not be enough training for participants who are not familiar with breathing techniques. The lack of experience could cause stress, feelings of anxiety or even hyperventilation. People who are more mindful could have more experience in performing diaphragmatic (abdominal) breathing and therefore benefit more from this technique. In follow-up research it could be interesting to investigate what effect multiple breathing trainings would cause. A final limitation of this study is that multiple researchers conducted the study. Although every researcher used the same protocol, it is possible there are differences between each researcher's style which might result in experimenter bias.

Conclusion

To conclude, this study investigated the effect of resonance breathing, tDCS and mindfulness on stress reactivity. This was measured by psychophysiological measurements (HRV and BP) and self-report measures (stress appraisal, negative affect, and positive soothing affect). The results of this study showed an effect of breathing condition where resonance breathing versus control breathing showed an increase in HRV and a decrease in BP. Moreover, the effect of breathing condition (slow versus controlled) showed a significant decrease in BP during the stress phase in participants with a high tendency towards mindfulness. No significant effects for PASA (stress appraisal) were found. Finally, high (compared to low) trait mindfulness was associated with less negative affectivity during all phases. However, this difference in negative affect between high and low levels of trait mindfulness was more strongly present during the stress phase. For positive soothing affect, mixed results were found regarding breathing condition and tDCS. Furthermore, high (compared to low) trait mindfulness was associated with more positive soothing affectivity during all phases. However, this difference in positive soothing affectivity between high and low levels of trait mindfulness was more strongly present during the stress phase. tDCS either showed null effects or counterproductive effects when combined with slow breathing and mindfulness.

References

Ahn, H., Zhong, C., Miao, H., Chaoul, A., Park, L., Yen, I. H., Vila, M. A., Sorkpor, S., & Abdi, S. (2019). Efficacy of combining home-based transcranial direct current stimulation with mindfulness-based meditation for pain in older adults with knee osteoarthritis: A randomized controlled pilot study. Journal of Clinical Neuroscience, 70, 140–145. https://doi.org/10.1016/j.jocn.2019.08.047

Allen, A. P., Kennedy, P. J., Dockray, S., Cryan, J. F., Dinan, T. G., & Clarke, G. (2017). The Trier Social Stress Test: Principles and practice. Neurobiology of Stress, 6, 113–126. https://doi.org/10.1016/j.ynstr.2016.11.001

Antal, A., Fischer, T., Saiote, C., et al. (2014). Transcranial electrical stimulation modifies the neuronal response to psychosocial stress exposure. Human Brain Mapping, 35,3750–9. doi:10.1002/hbm.22434.

Arch, J. J., & Craske, M. G. (2006). Mechanisms of mindfulness: Emotion regulation following a focused breathing induction. Behaviour Research and Therapy, 44(12), 1849–1858. https://doi.org/10.1016/j.brat.2005.12.007

Badran, B. W., Austelle, C. W., Smith, N. R., Glusman, C. E., Froeliger, B., Garland, E. L., Borckardt, J. J., George, M. S., & Short, B. (2017). A Double-Blind Study Exploring the Use of Transcranial Direct Current Stimulation (tDCS) to Potentially Enhance Mindfulness Meditation (E-Meditation). Brain Stimulation, 10(1), 152–154. https://doi.org/10.1016/j.brs.2016.09.009

Bhandari, P. (2022). Between-Subjects Design | Examples, Pros, & Cons. Scribbr. https://www.scribbr.com/methodology/between-subjects-design/

Baker, J. M., Rorden, C., & Fridriksson, J. (2010). Using Transcranial Direct-Current Stimulation to Treat Stroke Patients With Aphasia. Stroke, 41(6), 1229–1236. https://doi.org/10.1161/strokeaha.109.576785

Bates, D., Mächler, M., Bolker, B., & Walker, S. (2014). Fitting linear mixed-effects models using lme4. arXiv preprint arXiv:1406.5823.

Beck, A. T. (1979). Cognitive Therapy of Depression. Guilford Publications.

Benjamini, Y., & Hochberg, Y. (1995). Controlling the false discovery rate: a practical and powerful approach to multiple testing. Journal of the Royal Statistical Society. Series B (Methodological), 289-300. https://doi.org/http://dx.doi.org/10.2307/2346101

Bernston, G. G., Thomas Bigger, J., Eckberg, D. L., Grossman, P., Kaufmann, P. G., Malik, M., Nagajara, H. N., Porges, S. W., Saul, J. P., Stone, P. H., & Van Der Molen, M. W. (1997). Heart rate variability: Origins, methods, and interpretive caveats. Psychophysiology, 34(6), 623–648. https://doi.org/10.1111/j.1469-8986.1997.tb02140.x

Burg, J. M., & Wolf, O. T. (2012). Mindfulness as Self-Regulated Attention. Swiss Journal of Psychology, 71(3), 135–139. https://doi.org/10.1024/1421-0185/a000080

Burke, C. A. (2009). Mindfulness-Based Approaches with Children and Adolescents: A Preliminary Review of Current Research in an Emergent Field. Journal of Child and Family Studies, 19(2), 133–144. https://doi.org/10.1007/s10826-009-9282-x

Brownstone, N., Myers, B., & Howard, J. (2021). Psychological Tools to Assist Your Practice. Essential Psychiatry for the Aesthetic Practitioner, 189–199. https://doi.org/10.1002/9781119680116.ch18

Brown, K. W., & Ryan, R. M. (2003). The benefits of being present: Mindfulness and its role in psychological well-being. Journal of Personality and Social Psychology, 84(4), 822–848. https://doi.org/10.1037/0022-3514.84.4.822

Carpenter, R. (2016). A Review of Instruments on Cognitive Appraisal of Stress. Archives of Psychiatric Nursing, 30(2), 271–279. https://doi.org/10.1016/j.apnu.2015.07.002

Chrousos, G. P. (2009). Stress and disorders of the stress system. Nature Reviews Endocrinology, 5(7), 374–381. https://doi.org/10.1038/nrendo.2009.106

De Nederlandse Hartstichting. (2022). Lees alles over bloeddruk. Hartstichting. Geraadpleegd op 20 juni 2022, van https://www.hartstichting.nl/risicofactoren/gids-bloeddruk/wat-is-bloeddruk?tab=1

Dundas, J., Thickbroom, G., & Mastaglia, F. (2007). Perception of comfort during transcranial DC stimulation: Effect of NaCl solution concentration applied to sponge electrodes. *Clinical Neurophysiology*, *118*(5), 1166–1170. https://doi.org/10.1016/j.clinph.2007.01.010

Ehring, T., Zetsche, U., Weidacker, K., Wahl, K., Schönfeld, S., & Ehlers, A. (2011). The Perseverative Thinking Questionnaire (PTQ): Validation of a content-independent measure of repetitive negative thinking. Journal of Behavior Therapy and Experimental Psychiatry, 42(2), 225–232. https://doi.org/10.1016/j.jbtep.2010.12.003

Enkema, M. C., McClain, L. E., Bird, E. K., Halvorson, M. A., & Larimer, M. E. (2020). Associations Between Mindfulness and Mental Health Outcomes: a Systematic Review of Ecological Momentary Assessment Research. Mindfulness, 11(11), 2455–2469. https://doi.org/10.1007/s12671-020-01442-2

Feldman, G., Hayes, A., Kumar, S., Greeson, J., & Laurenceau, J.-P. (2006). Mindfulness and Emotion Regulation: The Development and Initial Validation of the Cognitive and Affective Mindfulness Scale-Revised (CAMS-R). Journal of Psychopathology and Behavioral Assessment, 29(3), 177–190. https://doi.org/10.1007/s10862-006-9035-8

Fertonani, A., Brambilla, M., Cotelli, M., Miniussi, C. (2014). The timing of cognitive plasticity in physiological aging: a tDCS study of naming. Frontiers in Aging Neuroscience, 6, 131. doi:10.3389/fnagi.2014.00131.

Fink, G. (2010). Stress Science [E-book]. Elsevier Gezondheidszorg.

Fitzgibbon, B.M., Kirkovski, M., Bailey, N.W., et al. (2017). Lowfrequency brain stimulation to the left dorsolateral prefrontal cortex increases the negative impact of social exclusion among those high in personal distress. Social Neuroscience, 12,237–41. doi: 10.1080/17470919.2016.1166154.

Frodl, T., & O’Keane, V. (2013). How does the brain deal with cumulative stress? A review with focus on developmental stress, HPA axis function and hippocampal structure in humans. Neurobiology of Disease, 52, 24–37. https://doi.org/10.1016/j.nbd.2012.03.012

Fox, J., Weisberg, S., Adler, D., Bates, D., Baud-Bovy, G., Ellison, S., ... & Monette, G. (2012). Package ‘car’. Vienna: R Foundation for Statistical Computing, 16

Gaab, J. (2009). PASA – Primary Appraisal Secondary Appraisal. Verhaltenstherapie, 19(2), 114–115. https://doi.org/10.1159/000223610

Gilbert, P., McEwan, K., Mitra, R., Franks, L., Richter, A., & Rockliff, H. (2008). Feeling safe and content: A specific affect regulation system? Relationship to depression, anxiety, stress, and self-criticism. The Journal of Positive Psychology, 3(3), 182–191. https://doi.org/10.1080/17439760801999461

Grossman, P., Niemann, L., Schmidt, S., & Walach, H. (2004). Mindfulness-based stress reduction and health benefits. Journal of Psychosomatic Research, 57(1), 35–43. https://doi.org/10.1016/s0022-3999(03)00573-7

Goilean, C., Gracia, F. J., & Tomás, I. (2021). Clarifying the relationship between trait mindfulness and objective performance. Current Psychology. https://doi.org/10.1007/s12144-021-02414-y

Guilliams, T., & Edwards, L. (2010). Introduction Chronic Stress and the HPA Axis: Clinical Assessment and Therapeutic Considerations. https://www.pointinstitute.org/wp-content/uploads/2012/10/standard_v_9.2_hpa_axis.pdf

Hassanzahraee, M., Nitsche, M. A., Zoghi, M., & Jaberzadeh, S. (2020). Determination of anodal tDCS duration threshold for reversal of corticospinal excitability: An investigation for induction of counter-regulatory mechanisms. Brain Stimulation, 13(3), 832–839. https://doi.org/10.1016/j.brs.2020.02.027

Hofmann, S. G., & Gómez, A. F. (2017). Mindfulness-Based Interventions for Anxiety and Depression. Psychiatric Clinics of North America, 40(4), 739–749. https://doi.org/10.1016/j.psc.2017.08.008

Horvath, J. C., Vogrin, S., Carter, O., Cook, M. J., & Forte, J. D. (2016). Effects of a common transcranial direct current stimulation (tDCS) protocol on motor evoked potentials found to be highly variable within individuals over 9 testing sessions. Experimental Brain Research, 234(9), 2629–2642. https://doi.org/10.1007/s00221-016-4667-8

Hurley, R., Machado, L. (2018). Using transcranial direct current stimulation to improve verbal working memory: a detailed review of the methodology. Journal of Clinical and Experimental Neuropsychology, 40, 790–804.
doi: 10.1080/13803395.2018.1434133.

J. Kabat-Zinn (1990). Full Catastrophe Living: Using the Wisdom of Your Body and Mind to Face Stress, Pain and Illness. Dell Publishing.

Jentsch, V. L., & Wolf, O. T. (2020). The impact of emotion regulation on cardiovascular, neuroendocrine and psychological stress responses. Biological Psychology, 154, 107893. https://doi.org/10.1016/j.biopsycho.2020.107893

Jonker, Z. D., Gaiser, C., Tulen, J. H., Ribbers, G. M., Frens, M. A., & Selles, R. W. (2021). No effect of anodal tDCS on motor cortical excitability and no evidence for responders in a large double-blind placebo-controlled trial. Brain Stimulation, 14(1), 100–109. https://doi.org/10.1016/j.brs.2020.11.005

Kabat-Zinn, J. (2015). Mindfulness. Mindfulness, 6(6), 1481–1483. https://doi.org/10.1007/s12671-015-0456-x

Katz, B. A., Lustig, N., Assis, Y., & Yovel, I. (2017). Measuring regulation in the here and now: The development and validation of the State Emotion Regulation Inventory

(SERI). Psychological Assessment, 29(10), 1235–1248. https://doi.org/10.1037/pas0000420

Kessler, S. K., Turkeltaub, P. E., Benson, J., & Hamilton, R. H. (2012). Differences in the experience of active and sham transcranial direct current stimulation. *Brain Stimulation*, *5*(2), 155–162. https://doi.org/10.1016/j.brs.2011.02.007

Khoury, B., Lecomte, T., Fortin, G., Masse, M., Therien, P., Bouchard, V., Chapleau, M.-A., Paquin, K., & Hofmann, S. G. (2013). Mindfulness-based therapy: A comprehensive meta-analysis. Clinical Psychology Review, 33(6), 763–771. https://doi.org/10.1016/j.cpr.2013.05.005

Khusid, M. A., & Vythilingam, M. (2016). The Emerging Role of Mindfulness Meditation as Effective Self-Management Strategy, Part 1: Clinical Implications for Depression, Post-Traumatic Stress Disorder, and Anxiety. *Military Medicine*, *181*(9), 961–968. https://doi.org/10.7205/milmed-d-14-00677

Kim, H.-G., Cheon, E.-J., Bai, D.-S., Lee, Y. H., & Koo, B.-H. (2018). Stress and Heart Rate Variability: A Meta-Analysis and Review of the Literature. Psychiatry Investigation, 15(3), 235–245. https://doi.org/10.30773/pi.2017.08.17

Kuznetsova, A., Brockhoff, P. B., & Christensen, R. H. B. (2017). lmerTest package: tests in linear mixed effects models. Journal of Statistical Software, 82(13).

Lenth, R. (2018). Emmeans: Estimated marginal means, aka least-squares means. R package version, 1(1).

Lehrer, P. M., & Gevirtz, R. (2014). Heart rate variability biofeedback: how and why does it work? Frontiers in Psychology, 5. https://doi.org/10.3389/fpsyg.2014.00756

Lehrer, P., Kaur, K., Sharma, A., Shah, K., Huseby, R., Bhavsar, J., & Zhang, Y. (2020). Heart Rate Variability Biofeedback Improves Emotional and Physical Health and Performance: A Systematic Review and Meta Analysis. Applied Psychophysiology and Biofeedback, 45(3), 109–129. https://doi.org/10.1007/s10484-020-09466-z
Lehrer, P. M., & Gevirtz, R. (2014). Heart rate variability biofeedback: how and why does it work? Frontiers in Psychology, 5. https://doi.org/10.3389/fpsyg.2014.00756
Ma, X., Yue, Z. E. J., Gong, Z., Zhang, H., Duan, N. Y., Shi, Y., Wei, G., & Li, Y. (2017). The Effect of Diaphragmatic Breathing on Attention, Negative Affect and Stress in Healthy Adults. *Frontiers in Psychology*, *8*. https://doi.org/10.3389/fpsyg.2017.00874

Mantzios, M., & Giannou, K. (2019). A Real-World Application of Short Mindfulness-Based Practices: A Review and Reflection of the Literature and a Practical Proposition for an Effortless Mindful Lifestyle. American Journal of Lifestyle Medicine, 13(6), 520–525. https://doi.org/10.1177/1559827618772036

March-Llanes, J., Marqués-Feixa, L., Mezquita, L., Fañanás, L., & Moya-Higueras, J. (2017). Stressful life events during adolescence and risk for externalizing and internalizing psychopathology: a meta-analysis. European Child & Adolescent Psychiatry, 26(12), 1409–1422. https://doi.org/10.1007/s00787-017-0996-9

Morgan, H., Davis, N. J., & Bracewell, R. M. (2014). Does Transcranial Direct Current Stimulation to Prefrontal Cortex Affect Mood and Emotional Memory Retrieval in Healthy Individuals? *PLOS ONE*, *9*(3), e92162. https://doi.org/10.1371/journal.pone.0092162

Mir-Moghtadaei, A., Caballero, R., Fried, P., Fox, M. D., Lee, K., Giacobbe, P., Daskalakis, Z. J., Blumberger, D. M., & Downar, J. (2015). Concordance Between BeamF3 and MRI-neuronavigated Target Sites for Repetitive Transcranial Magnetic Stimulation of the Left Dorsolateral Prefrontal Cortex. Brain Stimulation, 8(5), 965–973. https://doi.org/10.1016/j.brs.2015.05.008

Nederhof, A. J. (1985). Methods of coping with social desirability bias: A review. European Journal of Social Psychology, 15(3), 263–280. https://doi.org/10.1002/ejsp.2420150303

Nitsche, M. A., & Paulus, W. (2000). Excitability changes induced in the human motor cortex by weak transcranial direct current stimulation. The Journal of Physiology, 527(3), 633–639. https://doi.org/10.1111/j.1469-7793.2000.t01-1-00633.x

Nitsche, M. A., Boggio, P. S., Fregni, F., & Pascual-Leone, A. (2009). Treatment of depression with transcranial direct current stimulation (tDCS): A Review. Experimental Neurology, 219(1), 14–19. https://doi.org/10.1016/j.expneurol.2009.03.038

Nitsche, M. A. (2016). A technical guide to tDCS, and related non-invasive brain stimulation tools. Clinical Neurophysiology, 127(2), 1031–1048. https://doi.org/10.1016/j.clinph.2015.11.012

Peña-Gómez, C., Vidal-Pi.eiro, D., Clemente, I.C., Pascual-Leone,.., Bartr.s-Faz, D. (2011). Down-regulation of negative emotional processing by transcranial direct current stimulation: effects of personality characteristics. PLoS One, 6, e22812. doi:10.1371/journal.pone.0022812.

Perciavalle, V., Blandini, M., Fecarotta, P., Buscemi, A., Di Corrado, D., Bertolo, L., Fichera, F., & Coco, M. (2016). The role of deep breathing on stress. Neurological Sciences, 38(3), 451–458. https://doi.org/10.1007/s10072-016-2790-8

Petrocchi, N., Piccirillo, G., Fiorucci, C., Moscucci, F., Di Iorio, C., Mastropietri, F., Parrotta, I., Pascucci, M., Magrì, D., & Ottaviani, C. (2017). Transcranial direct current stimulation enhances soothing positive affect and vagal tone. Neuropsychologia, 96, 256–261. https://doi.org/10.1016/j.neuropsychologia.2017.01.028

Pickering, T. (1995). Stress and hypertension. American Journal of Hypertension, 8(4), 13A. https://doi.org/10.1016/0895-7061(95)97423-o

Raes, F. (2012). Repetitive Negative Thinking Predicts Depressed Mood at 3-Year Follow-up in Students. Journal of Psychopathology and Behavioral Assessment, 34(4), 497–501. https://doi.org/10.1007/s10862-012-9295-4

Rajendra Acharya, U., Paul Joseph, K., Kannathal, N., Lim, C. M., & Suri, J. S. (2006). Heart rate variability: a review. Medical & Biological Engineering & Computing, 44(12), 1031–1051. https://doi.org/10.1007/s11517-006-0119-0

Sala, M., Rochefort, C., Lui, P. P., & Baldwin, A. S. (2019). Trait mindfulness and health behaviours: a meta-analysis. Health Psychology Review, 14(3), 345–393. https://doi.org/10.1080/17437199.2019.1650290

Schmaußer, M., Hoffmann, S. O., Raab, M., & Laborde, S. (2022). The effects of noninvasive brain stimulation on heart rate and heart rate variability: A systematic review and meta-analysis. Journal of Neuroscience Research, 100(9), 1664–1694. https://doi.org/10.1002/jnr.25062

Schindler BA. Stress, affective disorders, and immune function. The Medical Clinics of North America. 1985 May;69(3):585-597. doi: 10.1016/s0025-7125(16)31034-3.

Shapiro, S. L., Brown, K. W., Thoresen, C., & Plante, T. G. (2010). The moderation of Mindfulness-based stress reduction effects by trait mindfulness: Results from a randomized controlled trial. Journal of Clinical Psychology, 67(3), 267–277. https://doi.org/10.1002/jclp.20761

Segal Z. V., Williams J. M. G., & Teasdale J. D. (2002). Mindfulness-based cognitive therapy for depression: A new approach to preventing relapse. New York: Guilford.

Staessen, J. A., Wang, J., Bianchi, G., & Birkenhäger, W. H. (2003). Essential hypertension. The Lancet, 361(9369), 1629–1641. https://doi.org/10.1016/s0140-6736(03)13302-8

Steffen, P. R., Austin, T., DeBarros, A., & Brown, T. (2017). The Impact of Resonance Frequency Breathing on Measures of Heart Rate Variability, Blood Pressure, and Mood. Frontiers in Public Health, 5. https://doi.org/10.3389/fpubh.2017.00222

Smith, A., Graham, L., & Senthinathan, S. (2007). Mindfulness-based cognitive therapy for recurring depression in older people: A qualitative study. Aging & Mental Health, 11(3), 346–357. https://doi.org/10.1080/13607860601086256

Smits, F. M., Schutter, D. J. L. G., van Honk, J., & Geuze, E. (2020). Does non-invasive brain stimulation modulate emotional stress reactivity? Social Cognitive and Affective Neuroscience, 15(1), 23–51. https://doi.org/10.1093/scan/nsaa011

Smits, F. M., Schutter, D. J. L. G., van Honk, J., & Geuze, E. (2020). Does non-invasive brain stimulation modulate emotional stress reactivity? Social Cognitive and Affective Neuroscience, 15(1), 23–51. https://doi.org/10.1093/scan/nsaa011

Tang, Y., Hölzel, B. K., & Posner, M. I. (2016). Traits and states in mindfulness meditation. Nature Reviews Neuroscience, 17(1), 59. https://doi.org/10.1038/nrn.2015.7

Tang, Y., Hölzel, B. K., & Posner, M. I. (2015). The neuroscience of mindfulness meditation. Nature Reviews Neuroscience, 16(4), 213–225. https://doi.org/10.1038/nrn3916

van Vreeswijk, M., Broersen, J., & Schurink, G. (2009). Mindfulness. Mindfulness En Schematherapie, 17–34. https://doi.org/10.1007/978-90-313-7587-5_3

Vanderhasselt, M., & Ottaviani, C. (2022). Combining top-down and bottom-up interventions targeting the vagus nerve to increase resilience. Neuroscience & Biobehavioral Reviews, 132, 725–729. https://doi.org/10.1016/j.neubiorev.2021.11.018

Weinstein, N., Brown, K. W., & Ryan, R. M. (2009). A multi-method examination of the effects of mindfulness on stress attribution, coping, and emotional well-being. *Journal of Research in Personality*, *43*(3), 374–385. https://doi.org/10.1016/j.jrp.2008.12.00

Woods, A. J., Antal, A., Bikson, M., Boggio, P. S., Brunoni, A. R., Celnik, P., Cohen, L. G., Fregni, F., Herrmann, C. S., Kappenman, E. S., Knotkova, H., Liebetanz, D., Miniussi, C., Miranda, P. C., Paulus, W., Priori, A., Reato, D., Stagg, C., Wenderoth, N., &