The effects of transcranial direct current stimulation on the reward related brain responses

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Abstract

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In this study we were interested in the effect of transcranial direct current stimulation (tDCS) on reward positivity. Reward positivity is an ERP component that reflects reward-related neuronal phenomena. The brain's reward system is related to the frontal asymmetry model, which divides approach and avoidance behaviour into separate hemispheres, with approach behaviour located in the left hemisphere and avoidance in the right. We speculated that this lateralized division could have an effect on reward-related neuronal functions. Hence we used this model as a framework for our setup and targeted anodal tDCS on the left dorsolateral prefrontal cortex (dlPFC) with an expectation that the stimulation would affect reward positivity. In earlier studies anodal tDCS stimulation of the left dlPFC has yielded promising results in the treatment of depression. However, the exact working mechanism of tDCS is currently unknown. What is known is that it affects the electrical charge of neurons but beyond that there is only speculation. In our study we gathered a total of 35 participants into the analyses consisting of 23 females and 12 males which we divided into two groups in random order: experimental group (n=16) and control group (n=19). We gave the experimental group real anodal tDCS into their left dorsolateral prefrontal cortex for ten minutes. To the control group we gave placebo stimulation, which means they only got stimulation at the beginning and the end of the ten minute procedure. After the stimulation, the participants played the "gambling doors task" -game where they had to choose between two doors from which they either gained or lost points. We collected EEG data during the game. Anodal tDCS did not have an effect on reward positivity. Instead, we did notice an effect on other ERP components, namely, N1 and P2. Another interesting occurrence was that the EEG amplitude stayed over the baseline P3 which we speculated to be late positive potential. According to our results it would seem that tDCS affects reactivity towards perceived stimuli rather than reward processing.

Keywords and abbreviations:

tDCS = Transcranial direct current stimulation, **Anodal tDCS**, **RewP** = Reward positivity, **N1**, **P2**, **LPP** = Late positive potential, **dlPFC** = Dorsolateral prefrontal cortex, **Frontal asymmetry**, **Gambling doors task**

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Tämän tutkimuksen tarkoituksena oli selvittää, onko aivojen transkraniaalisella tasavirtastimulaatiolla (tDCS) vaikutusta palkkiopositiivisuuteen (Reward positivity, RewP). Tällä palkkiopositiivisuudella tarkoitetaan tapahtumasidonnaista herätepotentiaalia (event-related potential, ERP) joka heijastaa aivojen palkkiojärjestelmän toimintaa. Aivojen palkkiojärjestelmän toimintaan liittyy frontaalisen asymmetrian malli, joka jakaa lähestymis- ja välttämiskäyttäytymisen vastakkaisille aivopuoliskoille. Lähestymiskäyttäytyminen sijoittuu vasemmalle puoliskolle ja välttämiskäyttäytyminen sijoittuu oikealle. Spekuloimme näiden lateralisoituneiden toimintojen vaikuttavan palkkioihin liittyviin neuronaalisiin prosesseihin. Täten käytimme tätä mallia viitekehyksenämme, ja kohdistimme anodaalista tasavirtastimulaatiota vasemmalle dorsolateraaliselle prefrontaalikorteksille odottaen, että stimulaatio vaikuttaisi palkkiopositiivisuuteen. Aikaisemmissa tutkimuksissa tähän aivoalueeseen kohdistetun anodaalisen tasavirtastimulaation on havaittu olevan tuloksellista masennuksen hoidossa. tDCS:n tiedetään vaikuttavan hermosolujen sähköiseen aktiivisuuteen, mutta muut vaikutusmekanismit ovat vielä epäselviä. Tutkimuksessamme lopullisiin analyyseihin sisällytimme 35:n koehenkilön tulokset, joista 23 oli naisia ja 12 miehiä. Koehenkilöt jaoimme satunnaisesti koe- (n=16) ja kontrolliryhmiin (n=19). Koeryhmä sai tasavirtastimulaatiota vasemmalle dorsolateraaliselle prefrontaalikorteksille kymmenen minuutin ajan. Kontrolliryhmä sen sijaan sai placebo-stimulaatiota, mikä tarkoittaa, että he saivat oikeaa stimulaatiota vain 30 sekuntia alussa ja lopuksi kymmenen minuutin jälkeen 30 sekuntia. Stimulaation jälkeen tutkittavat pelasivat “gambling doors task” -peliä, jossa tutkittavien tuli valita kahden oven välillä, josta he joko voittivat tai hävisivät pisteitä. Pelin aikana mittasimme tutkittavilta EEG:n. Tulosten mukaan anodaalisella tDCS:llä ei ollut vaikutusta palkkiopositiivisuuteen, mutta havaitsimme sillä olevan vaikutusta N1- ja P2-vasteisiin. Tuloksissa mielenkiintomme herätti myös koholla pysynyt amplitudi P3-vasteen jälkeen. Tämän spekuloimme olevan myöhäinen positiivinen potentiaali (late positive potential). Tuloksemme viittaavat tDCS:n vaikuttavan havaittujen ärsykkeiden reagointiin palkkioiden prosessoinnin sijaan.

Avainsanat ja lyhenteet:

tDCS = Transkraniaalinen tasavirtastimulaatio, **Anodaalinen tDCS, RewP** = Palkkiopositiivisuus, **N1**, **P2**, **LPP** = Myöhäinen positiivinen potentiaali, **dlPFC** = dorsolateraalinen prefrontaalikorteksi, **Frontaalinen asymmetria**, **Gambling doors task**

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Introduction

Major depression is a common mental health disorder that affects approximately 6 percent of the population each year (Kessler & Bromet, 2013; Depressio: Käypä hoito -suositus, 2022). Almost one in every five people suffers from at least one depressive episode in their lifetime (Bromet et al., 2011). According to ICD-10, symptoms of depression commonly include prolonged feeling of sadness, loss of interest and inability to enjoy activities that have previously been pleasurable (anhedonia), disorders relating to sleep, difficulties in concentration and self-harming thoughts and actions (Depressio: Käypä hoito -suositus, 2022). The criteria for diagnosis is that the symptoms have lasted at least two weeks. Depression is associated with various changes in the structure and functioning of the brain. Neuronal networks which are linked to emotional behaviour, are assumed to be pathophysiological factors of depression due to alterations in their grey matter volume and neurophysiological activity (Drevets et al., 2008). These networks include medial prefrontal cortex and areas in the caudolateral and medial orbital cortex, hippocampus, amygdala, and some ventromedial basal ganglia parts (Drevets et al., 2008)

Depression is often treated with either medication, psychotherapy or both (Malhi & Mann, 2018). Medical treatment is based around neurotransmitter regulation. Many antidepressants work by blocking transporter proteins which absorb neurotransmitters such as serotonin and norepinephrine back, preventing their reuptake (Kalat, 2017). The most common types of antidepressants include tricyclics, selective serotonin reuptake inhibitors (SSRI), serotonin norepinephrine reuptake inhibitors (SMRI) and monoamine oxidase inhibitors (MAOI). All of these have side-effects, such as heart irregularities, sleepiness, or increased blood pressure, and some of these can only be in a limited use to prevent health complications and may limit diets (Kalat, 2017). TMS (transcranial magnetic stimulation) is a neuronal modulation method that is used for the treatment of depression, and can act as an alternative to antidepressants. In clinical use for depression, TMS is targeted at the left dorsolateral prefrontal cortex for multiple sessions per day, which has yielded effective results (Sonmez et al., 2019). However, Sonmez et al. (2019) make note of the huge cost- and time requirement of TMS treatment. Transcranial direct current stimulation (tDCS) is another method of neuronal modulation that could be a more cost- and time efficient alternative to TMS, as it is less expensive and typically consists of fewer sessions in one day. In addition, the tDCS device can be taken home, so patients do not have to travel to a facility to get the treatment. It has a benefit of being a non-invasive brain stimulation (NIBS) method, along with TMS, therefore it requires no body-invasive use. tDCS works by feeding electrical

current through the scalp using two electrodes, to change neurons' resting potential. This method has yielded results in treatment of numerous mental and neuronal disorders, such as depression, multiple sclerosis, Alzheimer's disease and schizophrenia (Lefaucheur et al., 2017). Using tDCS has become a potential alternative to medication and TMS in treating depression. In a study conducted by Brunoni et al. (2017), tDCS was found to be more effective than placebo treatment but not as effective as escitalopram, which is an SSRI medicine. While it has not been shown to be as effective as antidepressants, its side effects are milder. The side effects have been found to only include slight tingling on the scalp underneath the electrode and a seeing a flash of light when the stimulation is suddenly turned on or off (Nitsche et al., 2003a). tDCS has been used in clinical treatment for depression by targeting the dorsolateral prefrontal cortex, of which functions has been thought to have a connection to depression (Aivojen tasavirtastimulaatio (tDCS) depression akuuttihoidossa: Käypä hoito -suositus, 2020; Koenigs & Grafman, 2009). This stimulation method has had a growing interest and it has been studied in the last few decades due to its capabilities in modulating neuronal activity, but its effects on the human neuronal circuitry and in treatment of depression is not precisely known yet (Utz et al., 2010).

1.1 The brain's reward system and its alterations in depression

Depression is associated with an abnormality in reward processing (Admon & Pizzagalli, 2015), which is believed to result in the decreased experience of pleasure and approach-related behaviour (Treadway & Zald, 2011). Indeed it has been observed that valence of prospective rewards and hedonic response are weakened in depression (O'Callaghan & Stringaris, 2019). Studies have found depressed patients to have hyposensitive responses to rewards and maladaptive responses to punishments, which are connected especially to abnormal function in the frontostriatal systems (Eshel & Roiser, 2010). The frontostriatal circuits are innervated by monoamines, such as GABA, glutamate and dopamine of which dopamine systems are related to the function of the reward system (Eshel & Roiser, 2010; Schultz, 2010). Mesocorticolimbic dopamine system, when functionally altered, could be responsible for some of the symptoms in depression such as anhedonia and amotivation, due to its connection to the reward system and having a role as a mediator of the hedonic value of stimuli (Martin-Soelch, 2009).

The activity of the right side frontal activity has been found to be increased in depression in relation to left frontal activity (Shenal et al., 2003; Kano et al., 1992; Schaffer et al., 1983). Relating to the former, the left and right frontal hemisphere are connected with approach- and

avoidance-related behaviour respectively (Davidson, 1984). This functional divide has led to a theoretical model of frontal asymmetry, which is applied and regarded in stimulation treatment. Because the left frontal area is related to approach-related behaviour, tDCS stimulation is usually targeted at the left frontal lobe around the dorsolateral area in clinical treatment (Aivojen tasavirtastimulaatio (tDCS) depression akuuttihoidossa: Käypä hoito -suositus, 2020).

EEG studies have been extensively conducted to observe brain activity in depressed patients. Several indicators have been used in these studies, of which event related potentials (ERP) are one of the most commonly used. Several ERP components are associated with depression, such as N1 and P2 which are suggested to be correlated with the serotonergic activity of the brain (Strobel et al., 2003; Linka et al., 2004). Reward positivity (RewP) is currently one of the most broadly used ERP components in studying the brain's reward system because it has been found to reflect its functioning. RewP has also been linked to depression, as it has been found to be decreased among depressed subjects (Proudfit et al., 2015; Burkhouse et al., 2017). It has also been found to be a predictive factor for increased depressive symptoms (Proudfit, 2015).

1.2 Reward positivity and the reward system

Reward Positivity (RewP) is a positive event-related potential associated with the reward system. Its neuronal components are located in the frontocentral areas of the brain. The positive amplitudes appear at the frontal central areas of the scalp at around 250-350 ms from a feedback stimulus (Tunison et al., 2019). An opposite phenomenon to RewP is a loss-related feedback appearing at around 250 ms called feedback negativity (FN) or feedback-related negativity (FRN; Yeung & Sanfey, 2004), from which RewP is derived from. However, RewP has been found to have larger positive amplitude, and therefore reflect processes of the reward system in gain- and win-related situations instead of losing or neutral situations (Holroyd et al., 2008). This positivity follows phasic dopaminergic signals from the midbrain into the anterior cingulate cortex (ACC) following an unexpected favourable outcome (Holroyd et al., 2008). Essentially, RewP and FRN are the same phenomenon but they are calculated on the contrary order from each other (RewP being calculated by subtracting losses from gains and vice versa for FRN; Proudfit, 2015). It is possible that RewP and FRN originate from different brain areas. Proudfit (2015) states that RewP is a better descriptor for a reward-related ERP component than negative feedbacks.

RewP is found to have a stronger amplitude when gains are unexpected, as it reflects a reward prediction error (Zhang et al., 2020). Also, according to Tversky & Kahneman (1992),

humans' reaction to losses is about twice as large in magnitude than reactions to rewards. The RewP amplitudes have been studied mostly using the gambling tasks with monetary rewards (Tunison et al., 2019; Hajcak et al., 2006; Holroyd et al., 2008; Proudfit, 2015). Recently, the phenomenon has been studied using non-monetary rewards such as points, social rewards and rewarding images, of which only rewarding points have elicited activity in the reward system (Flores et al., 2015; Brown & Cavanagh, 2018; Tunison et al., 2019). However, non-monetary reward based studies have not yielded as strong results as studies with monetary rewards, because the relative value of non-monetary rewards may be seen as less valuable as monetary rewards (Tunison et al., 2019). This would strengthen the premise that the outcome valence is indeed associated with the magnitude of RewP, and it is dependent on a relative value between possible outcomes (Holroyd et al., 2004).

Reward-related behaviour is regulated by dopamine through the mesolimbic and mesocortical dopamine pathways, (Baik, 2020). These pathways can be addressed together as the mesocorticolimbic pathway. These pathways span from the ventral tegmental area (VTA) to the limbic regions and to the prefrontal cortex and other cortical areas (Banich & Compton, 2018). Dopamine moving from VTA to the ventral striatum is an essential part of the mesolimbic pathway (Bjorklund & Dunnett, 2007). Together the mesolimbic pathway and VTA form a circuit that is active in reward-based behaviour. Nucleus accumbens (NAc) is a region located in the basal forebrain, and is a part of the ventral striatum (Heimer et al., 1999), that is associated with reward-related behaviour and motivation (Salamone et al., 2005). It is also an important component in the reinforcement system (Kalat, 2017). In the midbrain area, VTA and substantia nigra produce dopamine that moves to the NAc inside the basal forebrain via mesolimbic pathway. Together VTA and NAc form the VTA-NAc pathway, which is important in reward-related behaviour. (Nestler & Carlezon, 2006). Dorsal-lateral and dorsal-medial striatum are part of the basal areas, of which dorsal-lateral striatum is associated with the stimulus-response system, and dorsal-medial striatum with NAc are associated with goal-directed behaviour (Burton et al., 2015). The prefrontal cortex (PFC) has many functions, including reward-related decision making, comparing reward valence and motivation of decision making (Murray & Rudebeck, 2018). The reward-sensitive subdivisions of PFC include the dorsolateral prefrontal cortex (dlPFC), dorsal anterior cingulate cortex (dACC) and orbitofrontal cortex (OFC). The VTA projects dopamine directly into PFC via the mesocortical pathway, and the PFC in turn signals the ventral striatum (Chau et al., 2018). Therefore PFC differentiates rewards from non-rewards. Reward positivity is an electrophysiological response to PFC activating in a reward-related situation. The subcortical and prefrontal areas form the basis of the brain's reward system.

The prefrontal cortex (PFC) is important in reward-related decision making (Chau et al., 2018). Its reward-sensitive functions divide into three parts, the dorsal anterior cingulate cortex (dACC), ventromedial prefrontal cortex (vmPCF) and orbitofrontal cortex (OFC; Chau et al., 2018, Padoa-Schioppa & Assad, 2008; Rushworth & Behrens, 2008; Grabenhorst & Rolls, 2011). dACC is essential in predicting future rewards and changing behaviour according to them (Wittman et al., 2016). ACC is thought to be partly responsible in generating negative loss-related feedbacks, such as FN (Yeung & Sanfey, 2004), FRN (Cohen, et al., 2007), medial frontal negativity (Gehring & Willoughby, 2002) and feedback error-related negativity (Holroyd et al., 2006), due to them being present at the frontocentral area of the brain and near or in ACC. The vmPFC participates in encoding values and its impairment has been shown to lead into changes in making choices, especially into taking more risks (Damasio et al., 1996; Chau et al., 2018). vmPFC is involved in decisions relating to personal preferences, but it is not regarded as the area primarily in charge of this function (Chau et al., 2018). The OFC is characterized by encoding associations between stimulus and reward which are based on the earlier experiences (Chau et al., 2018; Padoa-Scioppa & Assad, 2008). The central OFC has also been claimed to be one component of the decision making process, but not included in the decision making itself, rather it contributes to this action (Chau et al., 2018). While vmPFC and OFC are both related to value encoding, Bouret & Richmond (2010) separate these two into separate functions: vmPCF specializes in internal factor information processing and OFC specializes in external factor information processing.

1.3 Frontal asymmetry

The frontal cortical areas that are in charge of the reward system function in an asymmetrical manner. The frontal asymmetry model divides avoidance and approach behaviour into separate hemispheral phenomena. Specifically, the frontal lobes have been found to be responsible in this model. According to this model, positive approach-related neuronal processes are primarily located in the left frontal area and negative avoidance-related processes are located in the right (Davidson, 1984). Especially frontal lobes are closely connected to reward-related emotional regulation (Davidson, 1993). In theory, the frontal asymmetry model suggests that emotional affection would activate the left or right frontal lobe depending on the affective emotion. Left-hemisphere damage may lead to dysphoric and depressive state (Davidson, 1984). However, Davidson (1993) argues that this frontal asymmetry does not have a dominant role in emotional regulation. The model has

been criticised for confusing affectional valence to motivation (Harmon-Jones, Gable & Peterson, 2010).

Cunningham et al. (2005) concluded that positive and negative stimuli elicit an event-related potential known as late positive potential (LPP) in opposite frontal areas. Therefore the affective valence of LPP can be positive or negative (Hajcak & Foti, 2020). Cunningham et al. (2005) discovered that positively valent social concepts evoked LPP around the left frontal area and negatively valent concepts evoked LPP around the right frontal area. Also, left side LPP was elicited from positive stimuli and right side LPP was elicited from negative stimuli (Cunningham et al., 2005).

Electrode positioning is important for the effects of tDCS (Nitsche & Paulus 2000). Due to the asymmetrical approach-system of the brain, excitatory stimulation of the left dlPFC area and inhibitory stimulation of the right could result in an increase in approach-related behaviour and, possibly, a stronger reward-related reaction. Indeed researchers have found that the right side hemisphere excitatory stimulation has a connection to decreased impulsivity (Lacey & Gable, 2021; Jacobson et al., 2011). Chrysikou et al., (2017) targeted anodal tDCS into the right dlPFC, which resulted in a decrease in approach-related behaviour during conflict situations. Also, right side excitation has been found to decrease risky decision making (Lacey & Gable, 2021; Fecteau et al., 2007). Hecht et al. (2013) concluded that left side excitatory and right side inhibitory stimulation resulted in making more immediate choices leading to smaller rewards instead of waiting for bigger rewards.

1.4 Transcranial direct current stimulation (tDCS) technique

Transcranial direct current stimulation (tDCS) is a neuromodulation method used to stimulate and alter brain activity non-invasively by conducting a weak electrical current of typically about 1-2 milliamperes (mA) through the scalp to the cortex (Brunoni et al., 2012). The electric current is conducted via two electrodes, a positively charged anode and a negatively charged cathode (Nitsche et al., 2003b; Bennabi & Haffen, 2018). The electrical current is conducted from one electrode into the other. The excitatory or inhibitory effect depends on the direction of the current (Nitsche et al., 2003b; Nitsche & Paulus, 2000). Anodal stimulation moves from the positively charged stimulating electrode (anode) into the reference electrode (cathode) increasing the electrical charge of the neurons. Cathodal stimulation works the other way with the electrical

current moving towards the negatively charged stimulation electrode (cathode) from the reference electrode (anode; Schlaug & Renga, 2008).

The function of tDCS stimulation is based on the polarisation of membrane potentials in cortical neurons in order to alter brain activity (Paulus, 2011). Anodal stimulation increases the neuron's resting potential, raising the electrical charge closer to the activation threshold to trigger action potentials making the neurons more likely to activate (Nitsche & Paulus, 2000). Cathodal stimulation does the opposite by lowering the resting potential further from the activation threshold causing hyperpolarization of the targeted neurons and making the neurons less likely to activate (Nitsche & Paulus, 2000). The long-term effect of tDCS on synaptic strength is thought to be caused by the changes in calcium and sodium channels; the glutamatergic neurons' plasticity and mechanisms of cellular membranes together are particularly essential factors (Liebetanz et al., 2002). Especially the pre-synaptic calcium-dependent channels seem to be affected, which alter the functioning of synaptic vesicles (Vasu & Kaphzan, 2022). The anodal stimulation increases the post-synaptic depolarization in the cellular membrane which leads to an enhancement in the pre-synaptic input caused by increase in the neuron's firing rate (Liebetanz et al., 2002). Liebetanz et al., (2002) suggest that NMDA receptors mediate the increase of synaptic strengthening by enhancing the post-stimulation firing spontaneity via an increase in the amount of Ca^{2+} level inside a neuron, hence the long-term effects.

An fMRI study showed that anodal stimulation increases activation in the motor cortex, although not significantly, and cathodal stimulation did not lower its activation but lowered its interconnected areas (Baudewig et al., 2001). The connectional effects have been noticed in the use of tDCS. Neuronal networks have a more sensitive response to direct current than individual neurons (Francis et al., 2003). Neuronal synchronisation, oscillatory effets and functional connectivity can be affected by tDCS (Lefaucheur et al., 2017). In addition to modulating synaptic potential, tDCS in general modulates the axons which may lead to non-synaptic effects that can have a contribution into its long-lasting after-effects (Ardolino et al., 2005).

In human studies, the maximum electrical current is set to 2 mA to guarantee safety (Iyer et al., 2005; Thair et al., 2017), though intensity up to 4 mA has been found to be safe in recent studies with some mild side effects (Chhatbar et al., 2017). It would appear that up to a certain point the longer the stimulation is given, the longer the effects in the brain last (Thair et al., 2017). The after-effects develop after stimulation has lasted at least 3 minutes and their duration increases as the stimulation's duration increases (Nitsche & Paulus, 2000). Commonly used stimulation time in studies is about 5-30 minutes which can lead up to 1-2 hours of after effects after stimulation (Bikson et al., 2009; Thair et al., 2017). There are findings that after a certain duration of anodal

stimulation the excitatory effects reverse. Monte-Silva et al. (2013) resulted in an inhibition after 26 minutes of continuous anodal stimulation in the motor cortex, which they suggested to be caused by an overflow of calcium that leads into a counter-regulation and inhibition.

1.5 N1-P2 complex and the late positive potential

According to several studies, increased depressive symptoms are correlated with decreased FN, and thus, decreased RewP amplitude (Foti & Hajcak, 2009; Liu et al., 2014). In addition to this, depression has been found to have a connection to other ERP components such as diminishment in N1 (van Dinteren et al., 2015) and increment in P2 (Shestyuk & Deldin, 2010). N1, or N100, is a negative ERP component peaking around 100 ms after stimulus onset. It has been associated with orienting to task-relevant stimuli (Luck et al., 1990). The component's peak has been found to be larger when attention is oriented towards a stimulus, compared to a stimulus elicited in a neutral or conditions of distributed attention (Vogel & Luck, 2000; Luck & Yard, 1995), perhaps indicating an ease in the processing of new stimuli. Peaking around 200 ms from stimulus onset is the component P2, or P200. P2 has been associated with memory-related processing, such as semantic processes (Federmeier & Kutas, 2002), working memory (Lefebvre et al., 2005; Wolach & Pratt, 2001) and performance of memory (Dunn et al., 1998). P2 has also been speculated to have a function in attention directed towards a certain stimulus (Hackley et al., 1990), early sensory encoding of objects (Dunn et al., 1998) and detecting their features (Luck & Hillyard, 1994). N1 and P2 components together form the N1-P2 complex, which is thought to be a manifestation of preattentional stage brain processes (Chernyshev et al., 2013).

P3, or P300 component peaks at around 300 ms from a stimulus. It has long been linked to awareness, as its amplitude peaks higher in aware conditions (Förster et al., 2020). The late positive potential (LPP) is an ERP component, which appears after P3, and is associated with emotion-arousing stimuli. Its amplitude is the strongest around the centroparietal area. Bradley (2009) concludes that LPP is a marker for stimuli that indicate something significant is happening in the environment. Appetitive and emotional systems become active from emotional stimuli, which results in LPP (Hajcak & Foti, 2020). LPP has also been linked with depression and it has been studied among depressed patients (Benau et al., 2019). Benau et al. (2019) found in their study, that depressed individuals' LPP was stronger in stimuli that were negative in valence compared to stimuli that were positive in valence.

Effects of tDCS have been studied on these ERP components. Anodal tDCS has been linked to an increase in N1 (Knechtel et al., 2014). Cathodal stimulation has also resulted in a stronger N1 over a temporo-parietal cortex (Zaehle et al., 2011). While tDCS appears to amplify N1, it has a reverse effect on P2. Csifcsak et al. (2009) found that cathodal tDCS weakened P2 amplitude when participants were subjected to pain. Similar results were shown in a study by Nitsche et al. (2012). There have been tDCS studies that have yielded effects on LPP, and studies that have found no effect on LPP. Sergiou et al. (2022) measured fifty male participants who had substance addiction and they received 20 minutes of High-Definiton tDCS stimulation of 2 mA two times a day on five consecutive days. According to their results tDCS targeted to the ventromedial prefrontal cortex affected LPP in neutral and aggressive pictures by increasing it (Sergiou et al., 2022). Faehling & Plewnia (2016) provided up to 28 minutes anodal stimulation with different intensities (maximum of 1,5 mA). Their results indicate that anodal tDCS stimulation of dlPFC has no effect on LPP (Faehling & Plewnia, 2016).

1.6 Research questions

Due to tDCS targeted at prefrontal areas having clinical results, and depression having a dampening effect on RewP, we are primarily interested to see if anodal tDCS targeted at the left dlPFC has an effect on RewP amplitude. This would be one of the explaining factors for the clinical results for the stimulation. Another point of interest is its possible effects on other ERP electrophysiological responses around the frontocentral area that are associated with neurological and psychiatric disorders. Therefore our research questions are:

1. Does tDCS have an effect on Reward positivity?
2. Does tDCS have an effect on any other ERP phenomenon?

We expect to see stronger amplitude in the feedback on the winning situations and weaker amplitude in the losing situations at around 250 ms, and we are interested in seeing how tDCS might affect these feedbacks.

2. Methods

2.1 Participants

2.1.1 Participant recruitment

Individuals who were in good health and aged between 18-50 years were recruited for the study. Exclusion criteria were the use of antidepressant, anxiety or beta-blocker medication. Migraine, epilepsy, pregnancy, brain damage and belonging to COVID-19 risk group were also exclusion criteria for participating, as well as, pacemaker, metallic implants in the scalp area, and skin problems on the scalp area of tDCS electrodes. Information about the experiment was distributed via email lists through which the recruitment of participants also took place. Ethical approval for the research was obtained from the Human Sciences Ethics Committee of the University of Jyväskylä. Prior to participating in the study, participants signed an informed consent.

2.1.2 Participants

45 participants were measured during 2020-2021. Before the EEG measurement they were randomly divided into experimental and control groups. Ten participants' EEG data were excluded from analyses because they had too much interference. The final number of participants therefore was 35 (experimental n=16, control n=19).

2.2 Experimental setup

2.2.1 tDCS

This study was conducted by applying tDCS on participants before they were measured with EEG. Participants received randomly either real stimulation (experiment group) or sham stimulation (control group). The real stimulation lasted for 10 minutes at 2 mA with the 30 second on ramp in the beginning and off ramp in the end. Control group that received sham stimulation got the real stimulation only in the beginning and in the end. During the ramp-up period the intensity of the stimulation gradually increased until it reached 2 mA intensity. After 10 minutes the intensity of stimulation immediately started decreasing for 30 seconds until it stopped. The anode was placed

on the F3 (left dorsolateral area) and the cathode on the F4 (right dorsolateral area). After tDCS stimulation, participants were measured with EEG while they played the gambling doors task game to measure their reward positivity. After the EEG measurement was conducted, the participants were informed whether they received the stimulation or not.

2.2.2 EEG and EOG

EEG and EOG were recorded at a sampling rate of 1000 hz with a low-pass filter on 0.1 -250 hz. We recorded EOG to take account of artefacts caused by blinking and eye movement. EOG electrodes were placed above and under the right eye and on to the side of both eyes. We used a ground electrode on the forehead and a reference electrode behind the right ear to separate the interference caused by other brain activity. We used Fz (frontal middle area), FCz (frontal central middle area), Cz (central middle area) and Pz (parietal middle area) channels in EEG to measure the activity in four different areas. The frontal channels have been shown to elicit higher amplitude in winning situations in numerous previous studies, such as Threadgill et al. (2020) and Cockburn & Holroyd (2018). Thus we expected to see RewP around the Fz, FCz and Cz areas. Pz acted as a comparison point, as RewP should not appear around the parietal area. For minimal interference from eye and body movement, the participants were asked not to blink or make large movements during the moments of choosing the door and gaining the feedback.

2.2.3 Gambling Doors Task

During EEG measurement, participants played the gambling doors task. Participants had to choose between two doors by pressing one of two buttons on a keyboard. One button opened the door that led to win and another opened the door that led to loss. The game started at 1000 points. One door supposedly awarded 200 points and the other one led to a loss of 100 points, but in truth it was completely random and it did not matter which door the participant chose. In total, there were 200 trials in the game of which 100 were wins and 100 were losses. After one second, the participant received feedback telling them whether they gained or lost points. Wins were marked by a green upwards pointing arrow and losses were marked by a red downwards pointing arrow. After the measurement was complete, the participants were informed that the game was randomised. We took the magnitude difference in reactions between rewards and losses (Tversky & Kahneman,

1992) into consideration by awarding twice the amount of points in winning situations to compensate for this difference.

2.3 Data analysis methods and grand average ERPs

2.3.1 Brain Vision Analyzer and Matlab

In Brain Vision analyzer, the EEG signal was low-pass filtered (<30 Hz) and segmented from -200 ms to 500 ms in relation to the onset of the feedback. Trials with excessive activity based on visual inspection were removed from further analyses. Using Matlab, trials were then averaged across participant, channel and trial type (gain, loss). The remaining trials were put into Matlab to create grand average ERPs for gains and losses and difference-ERPs for RewP.

2.3.2 SPSS

Because our participants had trials in differing conditions (gain and loss), they acted as their own control sample. The electrodes form another dependent variable, as the recorded EEG-signals share some of the same cortical functions. Therefore we have two dependent variables (repeated trials and electrodes), and hence, our main method of analysis was the repeated measures analysis of variance (rmANOVA) with group (stimulation/control) as a grouping factor and channel (frontal channels, which were an average of Fz, FCz and Cz, and parietal channel Pz) and condition (gain/loss) as within subject factors. Every component was calculated as a mean value of a certain time period. The rmANOVA was conducted separately for RewP (max value from 251-350 ms after stimulation), N1 (mean amplitude of 75-125 ms after stimulation), P2 (mean amplitude of 151-225 ms after stimulation) and LPP (mean amplitude 451-500 ms after stimulation). If there were any combined effects between two factors, we used the independent samples t-test for closer inspection.

2.3.3 Reward positivity

RewP has been defined as feedback appearing around 250 to 350 ms after a gain-related situation around the frontocentral cortical area. It is calculated by subtracting grand average loss ERP from grand average win ERP, resulting in a positive average amplitude in the frontal channels. ERP is

an average of all trials measured in the EEG. The win and loss trials are calculated into their own separate ERPs.

We deduced the existence of the reward positivity by comparing locations and conditions (win/loss). We compared the means of the frontal channels (Fz, FCz, Cz) to the mean of Pz channel between win and loss situations in the time period of 251 to 350 ms using the repeated measures rmANOVA. Because reward positivity should appear only in the frontal cortical area (Cockburn & Holroyd, 2018), we used the Pz channel as a reference because there should be no heightened amplitude after a reward related feedback in the parietal cortical area. To determine if tDCS stimulation had an effect on the reward system, a repeated measures rmANOVA was conducted to see if there is a difference between stimulation and control groups in ERP amplitude in the time period of when the reward positivity should appear.

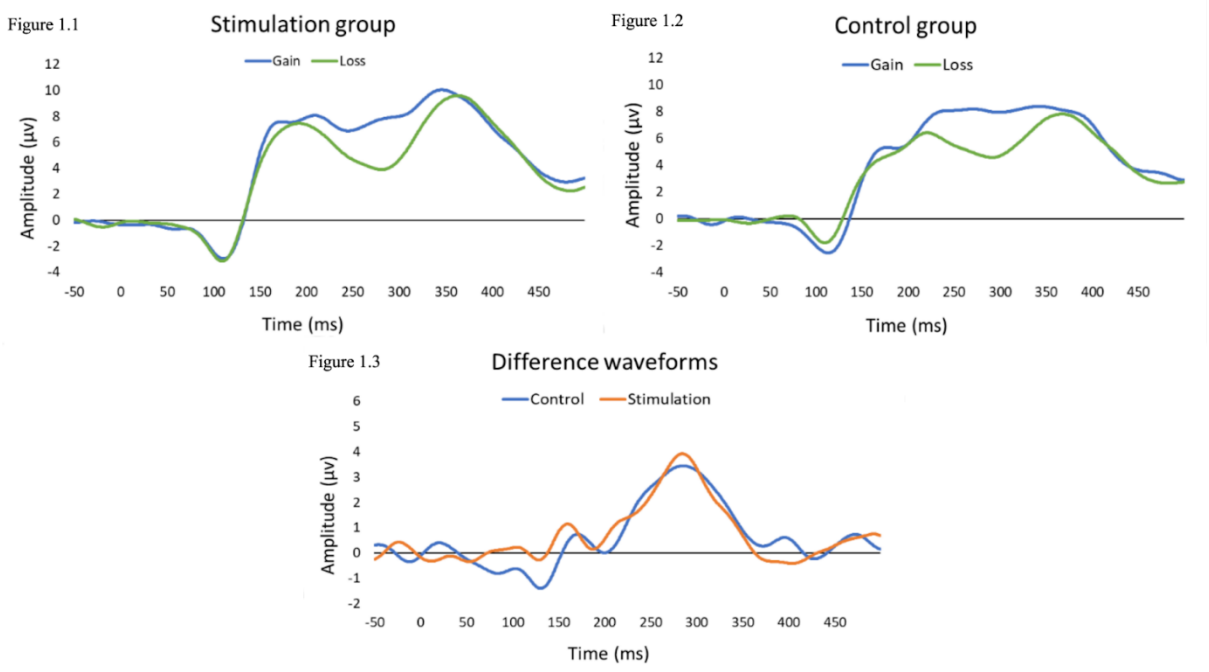
2.3.4 N1, P2 and late positive potential

While making the analysis, we noticed that there were differing amplitudes between stimulation and control groups before and after RewP. Specifically the N1 and P2 had differences in amplitude between the stimulation and control groups. Also after RewP, there was a heightened amplitude around 451 to 500 ms after feedback, which we assumed to be late positive potential (LPP). We also considered this in our analysis to find out what it could reflect. We included only frontal channels at this point of the analysis. To determine whether the stimulation affects N1, P2 and LPP, we used repeated measures rmANOVA. We used group (stimulation and control) and condition (gain and loss) as grouping variables. We compared groups (stimulation/control) separately in gain and loss situations and condition (gain/loss) separately in stimulation and control groups. Also we inspected the interaction of the group and condition with the independent samples t-test.

3. Results

3.1 RewP

There was a significant difference in amplitude between gain and loss conditions ($F(1, 33)=45.719$, $p < .001$, $\eta_p^2= .581$) and locations (Frontal channels and Pz channel) ($F(1, 33)=66.308$, $p < .001$, $\eta_p^2= .661$). No significant differences were perceived in amplitude between stimulation and control group ($F(1, 33)=.216$, $p=.645$, $\eta_p^2=.006$). Interaction of group and condition was not significant ($F(1, 33)=.001$, $p=.980$, $\eta_p^2 =.000$). For difference waveforms there was no significant difference between stimulation and control group ($t(33)=.358$, $p=.722$, $d=.120$) in the maximum amplitude during the 250 - 350 ms time period. These results indicate that reward positivity is more pronounced in the frontal area and is not affected by the stimulation.



Figures 1.1, and 1.2 show gain/loss ERPs (averaged from Fz, FCz and Cz channels) for the stimulation and control groups. The blue and green lines represent average gains and losses respectively. Figure 1.3 shows difference waveforms of stimulation and control groups. Difference waves from the stimulation and control groups were calculated by subtracting losses from gains. The orange line represents the stimulation group and the blue line represents the control group. The x-axis represents time from 50 ms before the stimulus

and its onset to 500 ms after stimulus onset, and the y-axis reflects the magnitude of the amplitude in microvolts.

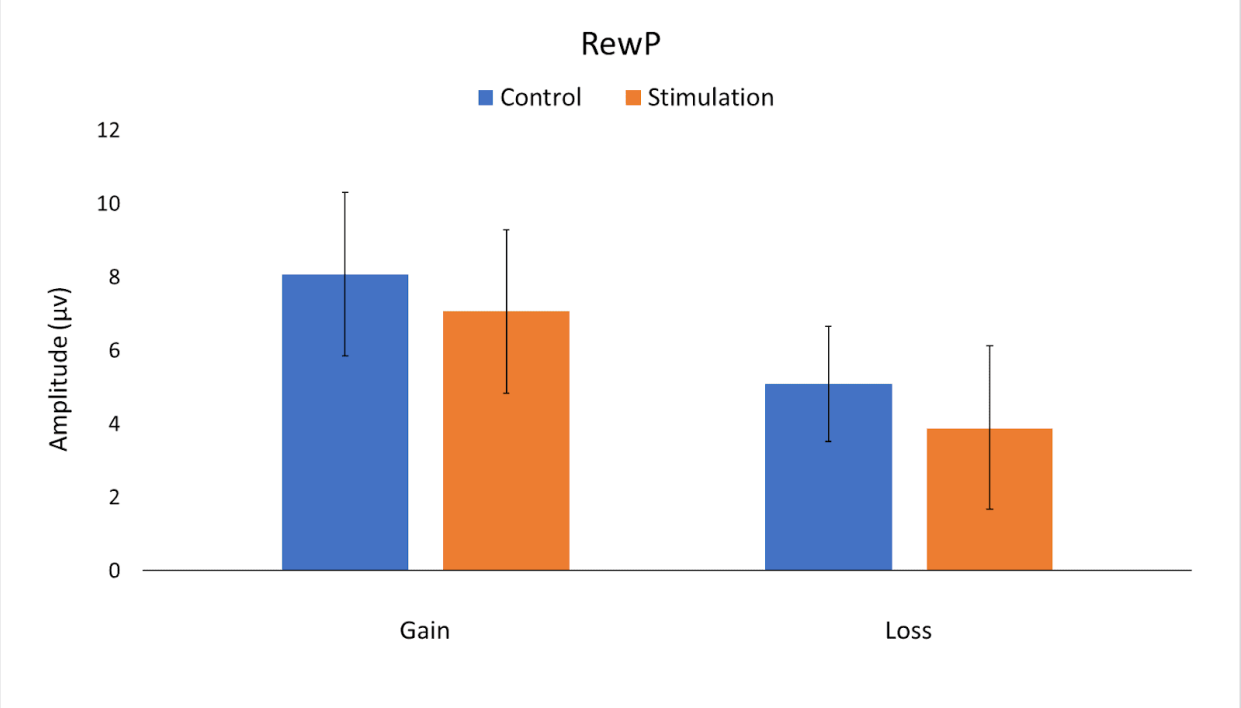


Figure 2. Response amplitudes in frontal channels (Fz, FCz, Cz) presented between groups (stimulation, control) and conditions (gain, loss) as mean values from a time period of 251-350 ms after stimulus (RewP). The x-axis represents the group (sham=control, stim=stimulation) and the y-axis represents the amplitude. Gain and loss conditions are coloured blue and green respectively. The gain condition has higher amplitude on both groups compared to the loss condition, however the groups aren't differing from each other in either condition.

3.2 N1

A significant interaction of group and condition factors ($F(1, 33)=4.198$, $p=.048$*, $\eta_p^2=.113$) was found. The stimulation had no significant effects ($F(1, 33)= 2.828$, $p=.102$, $\eta_p^2=.079$) on the minimum value from the time period of 75 - 125 ms. Conditions had no significant effect either ($F(1, 33)=3.199$, $p=.083$, $\eta_p^2=.088$). A significant difference was found between stimulation and control groups in N1 in the loss-situation ($t(33)=2.548$, $p=.016$*, $d=.851$), but not in the winning situation ($t(33)=.468$, $p=.643$, $d=.156$).

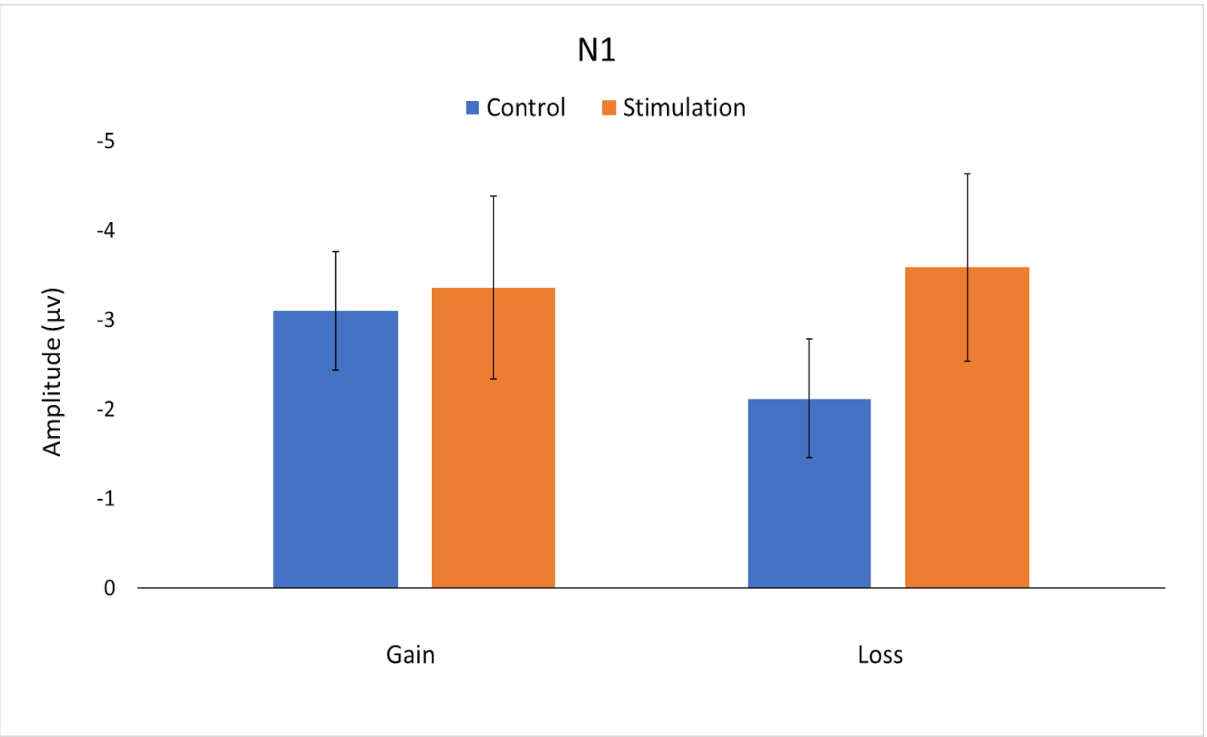


Figure 3. Response amplitudes in frontal channels (Fz, FCz, Cz) between group (stimulation, control) and condition (gain, loss) factors as mean values from a time period of 75-125 ms after stimulus (N1). The x-axis represents the group (sham=control, stim=stimulation) and the y-axis represents the amplitude. Gain and loss conditions are coloured blue and green respectively. In the loss condition, the stimulation group has a stronger negative amplitude than the control group. There is no significant difference between conditions in the stimulation group.

3.3 P2

The stimulation had a significant effect on the P2 amplitude ($F(1, 33)=6.178$, $p=.018$*, $\eta_p^2=.158$) in 151 - 225 ms time period. Condition had no significant difference ($F(1, 33)=.483$, $p=492$, $\eta_p^2=.014$), nor was there an interaction of group and condition factors ($F(1, 33)=.325$, $p=.572$, $\eta_p^2=.010$).

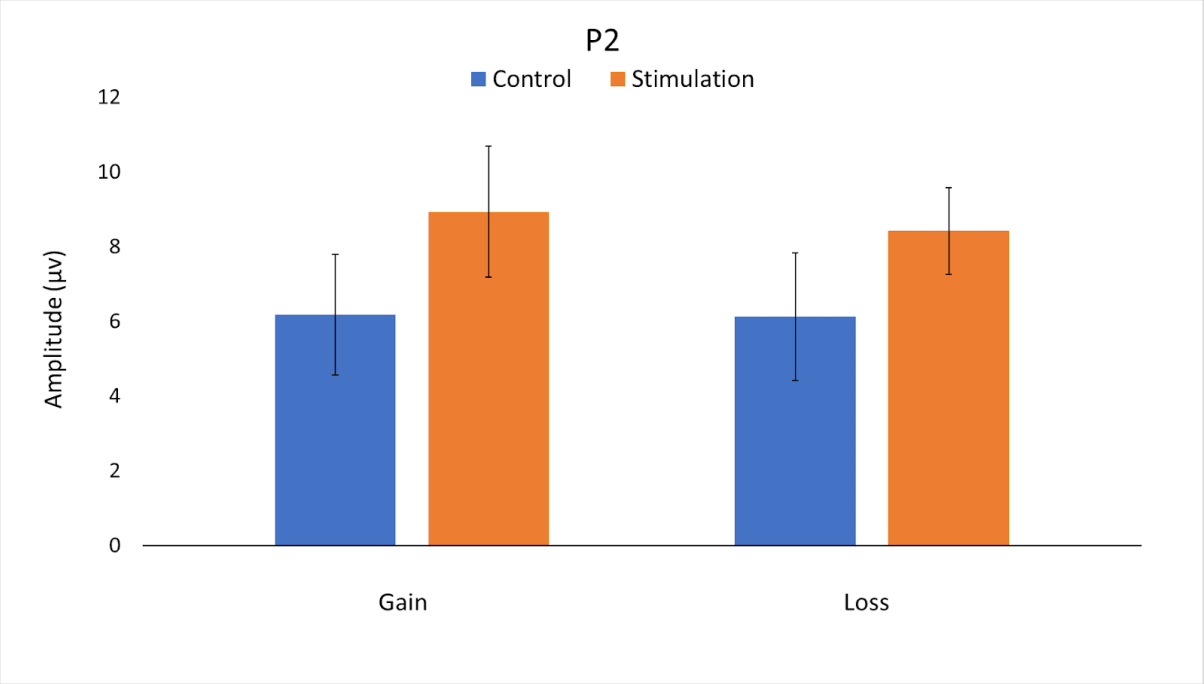


Figure 4. Response amplitudes in frontal channels (Fz, FCz, Cz) between group (stimulation, control) and condition (gain, loss) factors as mean values from the time period of 151-225 ms after stimulus (P2). The x-axis represents the group (sham=control, stim=stimulation) and the y-axis represents the amplitude. Gain and loss conditions are coloured blue and green respectively. The figure shows a difference between the stimulation and control groups. Amplitude is higher in the stimulation group compared to the control group in both gain and loss conditions.

3.4 LPP

In the time period of 451-500 ms, condition did have a significant difference ($F(1, 33)=46.961$, $p <.001$*, $\eta_p^2=.587$), with gains showing a higher amplitude. Stimulation did not have a significant difference on the amplitude of LPP ($F(1, 33)=.232$, $p=.633$, $\eta_p^2=.007$), nor was there an interaction between group and condition ($F(1,33)=.032$, $p=.859$, $\eta_p^2=.001$).

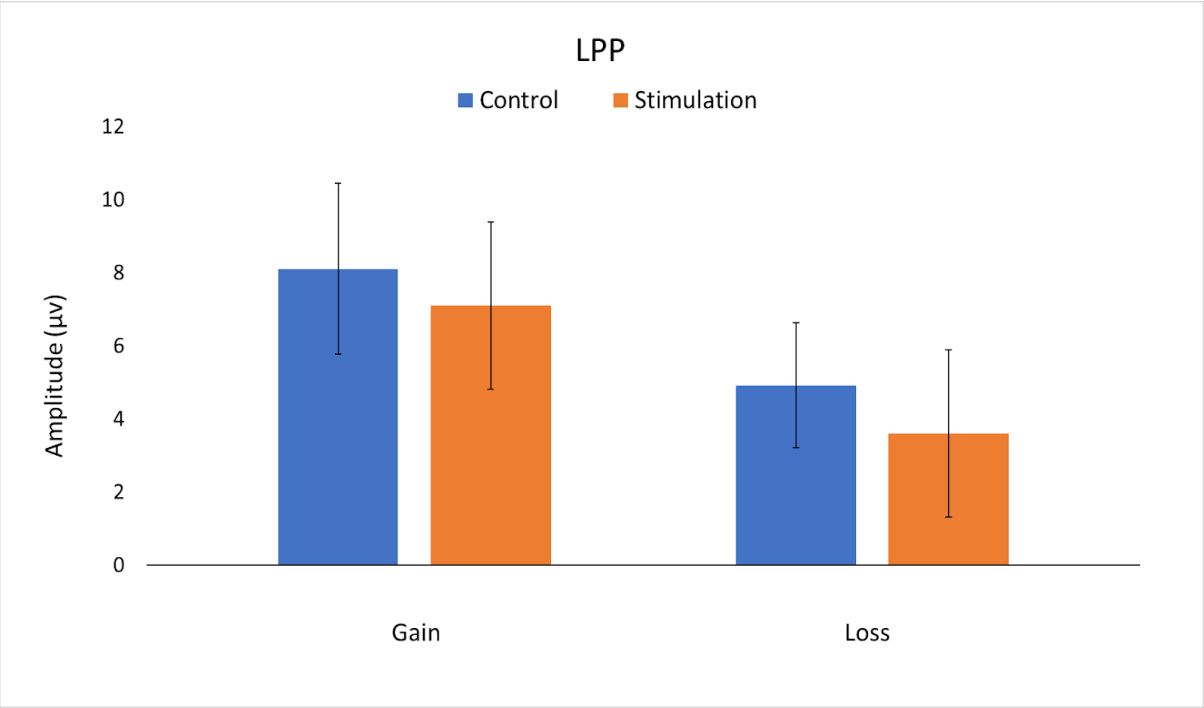


Figure 5. Response amplitudes in frontal channels (Fz, FCz, Cz) between group (stimulation, control) and condition (gain, loss) factors as mean values from a time period of 451-500 ms after stimulus (Late ERP). The x-axis represents the group (sham=control, stim=stimulation) and the y-axis represents the amplitude. Gain and loss conditions are coloured blue and green respectively. In the stimulation group, the loss condition had a lower amplitude than the gain condition.

4. Discussion

This study is about anodal tDCS stimulation of dorsolateral prefrontal cortex and its effects on reward positivity and other ERP components. Our primary expectation was that anodal stimulation would have altered neurons' or neuronal networks' activity around the left dorsolateral prefrontal cortical area, and hence, RewP would have had a difference in amplitude between stimulation and control groups. Reward positivity turned out to be unaffected by the tDCS, as no differences in RewP between stimulation and control groups were observed. While doing analysis it was found that stimulation affected N1 and P2 components. Stimulation had an effect on N1 in loss conditions but not in gain conditions, whereas stimulation had an effect on P2 in both conditions. LPP was also an object of interest, but the anodal tDCS stimulation had no effect on the component.

4.1 Reward positivity was not altered by anodal tDCS

In gain versus loss conditions, the positivity was stronger in the gain condition, meaning that RewP was observed the way it was expected to appear. The reaction was present in the frontal channels only, which was expected as well. The anodal stimulation on the left side dlPFC did not modulate neuronal functioning to a degree in which it would have altered the brain's reactivity to rewards. These results could indicate that tDCS does not affect emotional valence, but rather, it could affect something else. An alternative working mechanism for the stimulation's effectiveness could be an impact on approach-motivation instead of emotional valence (Harmon-Jones et al., 2010). In more recent studies, the asymmetrical frontal activity is thought to be a result of approach and avoidance motivation, rather than their respective affection (Harmon-Jones, 2004; Poole & Gable, 2014; van Honk & Schutter, 2006). According to Harmon-Jones et al. (2010), the left frontal area would activate from approach motivation, be it positive or negative in valence. In example, anger, which is negative in valence, has been found to cause this left sided activation as it can cause approach motivation (Harmon-Jones et al., 2010).

Positive versus negative affections have been long thought of as a single bipolar continuum (Cacioppo & Berntson, 1994). Instead more recent studies have suggested, and gained evidence which indicate, that the two affections are governed by different systems, one for positive emotions and one for negative emotions (Cunningham et al., 2005; Cacioppo & Berntson, 1994; Tellegen et al., 1999). This affective division could be coherent with the frontal asymmetry model. Therefore the emotional sensation might not be altered by exciting the left dlPFC, but the stimulation could still

affect the approach motivation. This could result in seeking more rewards, and thus, experiencing more of them as well. One of depression's main symptoms is a decrease in seeking pleasure (Lowes et al., 2021). Perhaps if anodal tDCS does have an excitatory effect on the left dlPFC, it could counteract the decreased effect of pleasure seeking in depression by increasing the approach-related neuronal systems.

If the neuronal circuits around the mesocorticolimbic pathway were excited, the hypodopaminergic symptoms could diminish. As Francis et al., (2003) stated, direct current affects neuronal networks rather than single neurons, resulting in excitatory stimulation of dlPFC also affecting its adjacent brain areas such as dACC, which is important in altering behaviour. This would then not increase the sensation of pleasure for rewards, but it would result in an increased behaviour and motivation to approach them, which could be one of the effective factors in tDCS treatment.

A new theory suggests that RewP would reflect a salience prediction error instead of a reward prediction error, as RewP has been reported to appear in physical punishment situations (Heydari & Holroyd, 2016). Heydari & Holroyd (2016) compared trials of shock punishment and shock omission and they noticed that RewP appeared larger in the punishment trials. This would imply that instead of us humans reacting to outcomes with emotional charge, we react to things we find notable such as reward and pain. However, there has been dispute over this theory, and some studies have had findings that oppose it such as a study conducted by Mulligan & Hajcak (2018) in which they dismiss the possibility of RewP reflecting salience prediction error presented in the study of Heydari & Holroyd (2016).

Prefrontal cortical functions include evaluating and recognizing possible rewards. Therefore an increased amplitude could be a signal of recognizing a reward and the following process of signalling deeper brain regions. This would be backed up by the increase of N1 and P2 amplitudes, which are associated with stimulus recognition. Perhaps RewP is another signal of this recognition process.

4.2 Effects on N1 and P2

On pre-attentional stage processes tDCS stimulation had a modulatory effect. Interestingly in our study, tDCS amplified N1 in the loss condition to the same level as in the gain condition. No amplification in the gain conditions was observed when we compare the stimulation and control groups, as the difference in amplitude between the two groups do not differ. Previous studies have given somewhat similar results considering the modulatory effects of the tDCS stimulation in the N1

component (Knechtel et al., 2014; Brosnan et al., 2018). For example Knechtel et al. (2014) conducted a study in which participants received 20 minutes of anodal tDCS stimulation into either left or right prefrontal cortex with an intensity of 2 mA, following an EEG measurement while listening to auditory stimuli in an oddball paradigm. Their results showed that N1 amplitude increased by the effect of stimulation regardless of which side of the dlPFC was stimulated (Knechtel et al., 2014). However, our experimental setup differs from that of Knechtel et al. (2014), as our focus was on N1 in winning and losing situations, whereas they focused on N1 in an auditory oddball paradigm. Interestingly our results indicate that tDCS stimulation has an effect on N1 only in losing situations and not in the winning situations. This condition-specific augmentation of the N1 amplitude implies an alteration in attentiveness specific only to losses.

The stimulation had an effect on P2, as the amplitude was increased in both conditions for the stimulation group. Previous studies have mainly given results related to the effect of cathodal stimulation, as it has been found to affect the P2 in a decreasing manner (Csifcsak et al., 2009; Nitsche et al., 2012). P2 has been shown to have a reversed connection to attentive processing and salience, meaning that the more attention is directed towards a stimulus, the lower the P2 peak appears to be (Straube & Fahle, 2010; Grasso et al., 2021). Straube & Fahle (2010) concluded that salience decreases the P2 amplitude. Balconi & Carrera (2011) speculate that P2 would be an indicator of processing multi-sensory information, which is affected by the information's consistency. Meaning that incoming inconsistent information decreases the P2 amplitude. This would indicate the P2 to be a marker of processing towards perceived stimuli, as more noticeable things cause the brain to work harder to understand that which is perceived, hence a lower amplitude. Higher amplitude P2 follows more simple and consistent stimuli, as they require less activity for processing and therefore more synchronous brain oscillations. This would release more capacity for other neuronal functions. All this considered, our results could reflect a change in outcome processing, perhaps an eased internalisation of perceived outcome, resulting from tDCS. Perhaps the ability to concentrate on target stimuli is eased as well, indicated by the amplification of P2. Grasso et al. (2021) speculate that anodal tDCS would reduce the effect of salient stimuli, increasing the P2 amplitude, which in turn would improve cognitive processing and increase neuronal excitability.

Neuronal synchronization has been related to neuronal communication and information processing, especially in memory-related processes (Fell & Axmacher, 2011). In encephalographic imaging, synchronization can be seen from the high amplitude that follows the neurons firing simultaneously, generating a larger electrical impact. The polarity of a peak (positive or negative) resulting from synchronization does not matter, as it always indicates neuronal synchrony. Reward positivity is one such component in which the neuronal synchronization is larger in winning

situations compared to losses, resulting in a positive difference waveform when comparing wins and losses. Desynchronization can be seen as a low amplitude in the encephalographic imaging when the brain processes new information. The low amplitude is a result of neurons activating separately, as opposed to synchronization, and therefore dropping in amplitude. Desynchronization is a result of an increase in cortical activity and information processing (Stam et al., 1993). These neuronal phenomena, especially desynchronization, are associated with attention-orienting processes, in which cholinergic and noradrenergic activity prohibits the brain's rhythmic functioning which in turn improves interneuronal communication (Soininen & Riekkinen, 1993).

According to Crowley & Colrain (2004), when N1 peak amplifies, the P2 peak typically diminishes. Our study yielded an opposite effect in the loss condition as a result of the stimulation, as N1 amplitude's increase was followed by an amplified P2 in the stimulation group. As Francis et al. (2003) stated, tDCS modulates the activity of neuronal networks instead of single neurons, it could be possible that the alterations in N1-P2 complex as a whole could be due to effects of excitation of neuronal networks that connect to the OFC and vmPFC. These areas are linked to value encoding, which could, when modulated, cause an amplification of N1 and especially P2, as these components are linked to encoding functions and feature detection and appear to be modulated in reward-related situations (Luck & Hillyard, 1994; Dunn et al., 1998; Folyi et al., 2016). Our results indicate that anodal tDCS seems to affect the N1-P2 complex in an amplifying manner. This would refer to the stimulation strengthening the preattentional stage processes, which in turn frees capacity for other processes increasing the N1 and P2 amplitudes. When attentiveness is increased, N1 peak is amplified and the following P2 peak is often decreased and vice versa (Crowley & Colrain 2004). Therefore, attention oriented towards an elicited stimulus should lead to a more active neuronal processing, which results in an amplified N1 and decreased P2. The decrease in P2 could imply that the brain is still processing the perceived information. Therefore it would result in less synchronous neuronal activity in the semantic processing and more active processing that is left over from orienting towards the perceived stimulus in N1.

4.3 Late positive potential was only modulated by win/loss conditions

We noticed a heightened amplitude over the baseline after P3 at around 450 ms onwards, which we assume to be LPP as previous studies have found LPP to be elicited from emotion-arousing stimuli (Cunningham et al., 2005; Bradley, 2009; Hajcak & foti, 2020). In our results LPP was amplified in the gain condition compared to the loss condition. This result is similar to an earlier research, where

LPP has been found to be stronger when elicited by positively valent stimuli (van Strien et al., 2010). In addition, van Strien et al. (2010) found LPP to be higher in positively valent faces compared to negatively valent ones, and Cunningham et al. (2005) found LPP to be elicited from both positively and negatively valent social concepts. Our results were consistent with the aforementioned studies as the LPP was elicited in both conditions, and in the gain condition the amplitude was stronger compared to the loss condition. Essentially this result was similar to what we had for RewP, though the difference in amplitude between the two conditions was smaller in the case of LPP. We then took interest in the possibility of the stimulation affecting this amplitude. However as with RewP, LPP was not affected by anodal tDCS. The lack of impact from tDCS was to be expected based on earlier research, such as one made by Faehling & Plewnia (2016) in which tDCS had no effect on LPP. Sergiou et al. (2022) gave High-Definition tDCS to their participants at a 2 mA intensity twice a day for five consecutive days, which increased their LPP. It would seem that longer repeated periods of stimulation could affect LPP's amplitude more effectively. Our one time 10 minute stimulation may not have been enough to have an effect on LPP. In addition to the working mechanisms of conventional tDCS, High-Definition tDCS has more concentrated and longer lasting effects on neuronal activity (Parlikar et al., 2021).

It seems that LPP is a marker of salience due to its presence with stimuli relating to essential needs for survival of oneself and continuation of one's species (Briggs & Martin, 2009; Weinberg & Hajcak, 2010). Things we perceive as salient will elicit stronger LPP, such as faces, social and erotic concepts (Ferri et al., 2012), appetition (Hajcak & Foti, 2020) or winning and losing. It appears to be a broad signal of pleasant or unpleasant emotion-arousing perception. Ferri et al. (2012) also found that LPP was stronger in neutral images containing people or faces when compared to neutral images with no people or faces, and threatening images that did or did not contain faces elicited stronger LPP than neutral images without faces. It would seem that LPP is related to essential requirements, such as appetite and social needs. Stimuli that elicit larger LPP are perceived as salient because they are a prerequisite for our survival.

4.4 Result generalisation and future research

This study investigated whether one time 10 minute tDCS stimulation has an effect on the brain's reward system. tDCS has had mixed results in different studies, as some have discovered significant results and some have found none. According to Hecht et al. (2013) electrode placement, size and the intensity of the current have a major effect in tDCS trials. As tDCS in

clinical use and studies usually target the left dlPFC, it could affect neuronal activity in only one side of the brain. Though the brain typically does funcion asymmetrically regardless of being stimulated or not, the stimulation's influence over the hemispheres' individual activity could be witnessed in an experimental and control group setup. Separate experimental groups for individual hemispheres could yield differing results and could be compared to a control group. Smaller electrode size creates a stronger effect on a narrower area, while bigger electrodes would have a milder effect on a broader area (Hecht et al., 2013; Nitsche et al., 2007). Therefore strong electrical current targeted at a large area of effect may yield different results than a weaker and more condensed current. In this study, the electrical current was set to 2 mA which is commonly used in studies and treatment. Another intensity could have a different effect, and thus yield different results. The effects of tDCS stimulation on humans have been studied with an intensity of 4 mA (Chhatbar et al., 2017). They found 30 minutes of 4 mA tDCS stimulation to be safe and tolerable with stroke patients. As a negative side effect, they found it to cause transient skin redness with 50% of participants (Chhatbar et al., 2017). Also the duration of the stimulation and the number of stimulation repetitions are significant factors. Studies, in which there have been multiple stimulation sessions or longer duration have yielded different results to ours. For example, Sergiou et al. (2022) had changes in LPP in their setup. A single 10 minute session might not be enough to modulate neuronal activity. The stimulation's duration and the frequency of use is a factor to consider for future studies. Longer duration of stimulation or several times of its repetition could manifest on the reward system differently or more broadly on event related potentials.

Though we had a plentiful number of participants, our sample size was too small to make reliable conclusions and the sample consisted mostly of females. For future studies more participants should be recruited to gain better results. Our sample was homogenous to a point where possible significant results might not be applicable to make a difference in the results. All our participants were in primary health, meaning that there were no participants with depression, epilepsy or other conditions that would possibly affect their EEG-results. In non-depressed participants, as in our sample, it might be that the reward system already functions at a level that cannot be elevated anymore, thus leading to a ceiling effect in the present study. Participants with depression or other mental disorders could have a lower baseline level of reward processing and would thus be more responsive to putative effects of tDCS.

All the EEG electrodes that we used were placed in a central position across the scalp. Three of them (Fz, FCz and Cz) targeted the frontal area which we were interested in, and one (Pz) functioned as a reference. Due to our electrode placement, we could only make conclusions about neuronal activity located in the middle of the scalp at specific points. No data was gathered from

the left and right sides. Therefore we could not observe the effects of tDCS from these areas. This leaves the frontal asymmetry model out of our field of closer observation and applicable only as a theoretical framework. More electrodes especially around the side areas could yield broader results and possible lateral differences. More channels would also allow for more advanced pre-processing (including artefact removal) and analysis methods in general.

The participants were awarded more points in the gain condition than what they lost in the loss condition, which affected the relative magnitudes between wins and losses. This difference was made to compensate for humans' reactions to losses being stronger than to reactions to rewards (Tversky & Kahneman, 1992). However it's difficult to say whether doubling the profits balances the magnitude of reaction between gains and losses. In this study, the gambling doors task was implemented in a way that the participants couldn't see their total score. Gaining and losing points in single trials without information of total score can create an impression of separate trials which are disconnected from each other, which can be beneficial for studying a single outcome's impact without additional factors. These additional factors could interfere with the value of rewards. If participants saw their total scores, it could affect the outcome's emotional valence. When one is low on points, gains and losses might feel more impactful due to the change in the percentual amount of points, generating a stronger response. Non-monetary rewards were applied in this study which may have had an effect on the magnitude of the RewP. Earlier studies have found monetary rewards to cause increased RewP amplitudes compared to non-monetary rewards (Tunison et al., 2019; Flores et al., 2015; Weinberg et al. 2014). In low risk/reward situations humans tend to not react as strongly to losses as in high risk/reward situations as the amount of loss is not significant. It would be interesting in the future to explore how tDCS stimulation could affect neuronal reactivity to monetary rewards.

In the future research, it would be essential to study the impact of tDCS on depressed patients as depression has been found to reduce neuronal reactivity, which tDCS seemingly increases through N1 and P2. Also, it would be fascinating to focus on the N1 and P2 components. For instance how tDCS might affect especially P2 when incongruent stimuli are presented, such as conflicted emotional signals e. g. combining happy tones of voice and angry face images. Our results of RewP and LPP were similar, as gain conditions elicited larger amplitudes than loss conditions. LPP has been found to be diminished in depressed children, adolescents (Grunewalt et al., 2019) and in adults (Hajcak & Foti, 2020). Perhaps RewP and LPP are neurologically connected as they are both associated with emotion arousing stimuli e.g. rewards, though LPP is not elicited only by rewards. This could be a topic for future research.

Depression has an impact on the blood flow and glucose metabolic activity. More depressed state leads to lesser left frontal glucose metabolic activity and less blood flow (Baxter et al., 1989; Drevets et al., 1992). Negative life-events affect right frontal activation in an increasing manner and decrease the left frontal activation (Davidson, 1993). Perhaps the alterations from tDCS on this metabolic activity in addition to neuronal functioning could be studied.

Each person's brain is anatomically unique. The same brain areas largely correspond to the same functions between individuals, but small differences do exist in their structures, meaning that electrodes positioned in a certain place in one individual's scalp yield certain results but when the same electrode is placed on the same place in another individual's scalp, the result may be different. Small anatomical differences in the brain between individuals can cause big differences in the results. This is a universal issue in the field of neuroscientific study.

Conclusions

Results of this study do not support the premise that tDCS would affect the reward system. Stimulation and control groups did not differ significantly from each other at the 250–350 ms after stimulus onset. Therefore we can conclude that tDCS had no influence on reward-related neuronal circuitry (but the study should be replicated with depressed individuals). Rather, it seems to affect reactivity towards stimuli.

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