The role of cognitive control in prosocial behavior – Investigating the neural foundations of retribution and forgiveness

Dissertation

Zur Erlangung des Grades eines Doktors der Naturwissenschaften

der Mathematisch-Naturwissenschaftlichen Fakultät und der Medizinischen Fakultät

der Eberhard-Karls-Universität Tübingen

vorgelegt von

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Mai 19

Tag der mündlichen Prüfung: 28.10.2019

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“What is forgiveness? An emotion? A coping mechanism? An element of deepest faith? A way for the heart and soul to combat the type of hate, anger, rage and a thirst for revenge that could ultimately consume a person? All of those and more?”

Mike Barnicle

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ABBREVIATIONS

ACC	Anterior Cingulate Cortex
cTBS	Continuous Theta Burst Stimulation
DLPFC	Dorsolateral Prefrontal Cortex
EMG	Electromyography
fNIRS	Functional Near-Infrared Spectroscopy
HHb	Deoxygenated Haemoglobin
IFG	Inferior Frontal Gyrus
iTBS	Intermittent Theta Burst Stimulation
O_2Hb	Oxygenated Haemoglobin
PFC	Prefrontal Cortex
TBS	Theta Burst Stimulation
TMS	Transcranial Magnetic Stimulation

SUMMARY

Forgiveness is a highly relevant ability for a satisfied life with long-lasting relationships. It is hypothesized that cognitive control enables forgiveness through the inhibition of baser revenge seeking feelings. For investigating the exact underlying mechanisms, a set of four studies was run. In order to study the ability to forgive, the participants first played an ultimatum game, in which they learned that some opponents are fair and some are unfair. Following this implicit learning experience the roles were changed and in a subsequent dictator game the participants had to split up money between themselves and the opponents of the previous game. Regarding the previously unfair opponents they had to decide if they wanted to forgive (with allocating a fair amount of money) or to take revenge (with allocating an unfair amount of money). This paradigm sequence was combined in a first study with inhibitory theta-burst stimulation of the right dorsolateral prefrontal cortex (DLPFC), resulting in the causal conclusion that cognitive control is needed for forgiveness processes as after the stimulation the participants were significantly more revenge seeking. In another study, participants with high and low cognitive control were compared. Participants with low cognitive control were significantly more revenge seeking, whereas, participants with high cognitive control were less revenge seeking. Concluding from the results of a regression analysis this difference was (partly) caused by different emotional foundations of the behavior, with sympathy as a relevant factor in the high cognitive control group and revenge in the low cognitive control group. In a third study the gaming paradigms (ultimatum game and dictator game) were used in combination with activating theta-burst stimulation of the right DLPFC in a highly impulsive group which is known to be more revenge seeking than the average. With higher activation in the right DLPFC it was not possible to increase the forgiveness behavior towards the unfair opponents. Surprisingly, the activating neuromodulation increased the generosity towards fair opponents. In an additional study with a different paradigm the ability of emotion regulation (which is assumed to be a key player in forgiveness processes) in participants with low vs. high cognitive control was measured. It was shown that participants with low cognitive control failed, especially in implicit emotion regulation which is essential for daily life forgiveness processes. Based on these results a forgiveness model is proposed. According to this model the probability to forgive a wrongdoer is influenced by cultural/cognitive response tendencies and state/trait emotional tendencies. Cognitive control especially, but also the experienced emotions play a crucial role in forgiveness processes according to this model.

1. INTRODUCTION

This thesis is about the neural foundations of forgiveness and integrates four different papers with specific foci. In the first section the two key concepts – forgiveness and cognitive control – are introduced. Second, the used paradigms and main methods (functional near-infrared spectroscopy (fNIRS) & transcranial magnetic stimulation (TMS)) are described briefly. In a third section the four studies are contextualized, and it is explained why the different studies were run. In the discussion section a new forgiveness model is introduced, and limitations and further directions are discussed.

1.1. FORGIVENESS

1.1.1. DEFINITION

Especially for psychologists, theologians and philosophers, forgiveness is a highly relevant concept. These different disciplinary perspectives highlight the fact that there is no universal definition of what forgiveness exactly is. In general, forgiveness can be classified in the following three dimensions: orientation (self vs. others), direction (active increasing of positive experiences vs. passive letting go of negative experiences) and the form (emotion vs. cognition) (cf. Lawler-Row, Scott, Raines, Edlis-Matityahou, & Moore, 2007). Pingleton (1989) describes forgiveness as an act against the natural and reflexive talion principle; therefore, it is hard to predict and needs specific resources. DiBlasio and Proctor (1993) describe forgiveness as a healing of inner emotional wounds and a reestablishing of the relationship to the offender. For being able to do so, it is necessary to suppress negative judgements and affects by viewing the provocateur with empathy and affection (Enright, 1991). The process of forgiveness is described by Denton and Martin (1998) as an inner process of the victim with reducing negative, revenge inducing emotions such as anger and resentment with the result that the wish for revenge is no longer determinative. Depending on the involved persons and the situation, this can be a time-consuming process (Sells & Hargrave, 1998). In a more tangible way, Wilkowski, Robinson, and Troop-Gordon (2010) describe forgiveness as a combination of two processes which merge fluently; first, the decision to forgive the provocateur and second, the inhibition of negative, revenge seeking emotions.

1.1.2. RELEVANCE

The concept of forgiveness has received increased attention during the last decades. In 1980 no publication with the keyword forgiveness was published on PubMed. Since then, nearly every year featured an increased number of papers about forgiveness. In 2018, 84 papers were published on this topic. This illustrates the growing attention forgiveness has received as a relevant topic for scientific inquiry over the last years.

In a meta-analysis, Lee and Enright (2019) propose a positive correlation between forgiveness and physical health. Higher rates of forgiveness were shown to be correlated with a better physical health; no supplementary moderator effects were found. The authors explain this clear result with the following mechanism; unforgiveness is strongly associated with negative emotions such as anger, bitterness and hate (Harris & Thoresen, 2005). Anger especially is known for its negative influence on (particularly cardiovascular) health (Gallo & Matthews, 2003). Stress, induced through these negative emotions can induce a chronic hyperarousal of the sympathetic nervous system which affects the endocrine production (Thoresen, Harris, & Luskin, 2000). Additionally, these negative emotions are known to cause rumination (Worthington & Scherer, 2004), which is strongly associated to depression (e.g. Rosenbaum, Thomas, et al., 2018). Successful forgiveness, in contrast, reduces these negative emotions and entails an increase of positive emotions such as sympathy, compassion or love (Worthington & Scherer, 2004).

Furthermore, for a desirable social life forgiveness seems to be a relevant factor. Flanagan, Hoek, Ranter, and Reich (2012) found in a sub sample of adolescent students a positive correlation between forgiveness/conflict resolution and support seeking strategies. Additionally, a negative correlation between social anxiety and forgiveness was found. Wai and Yip (2009) found also in adult participants a positive correlation between forgiveness and general psychological well-being, especially interpersonal adjustment. Interpersonal adjustment describes the ability of someone to establish positive relationships to others and to receive support from them (Summerfeldt, Kloosterman, Antony, & Parker, 2006). Considering the influence of forgiveness on marital relationships, inconsistent results were found. On the one hand, Fincham, Beach, and Davila (2004) found positive correlations between the satisfaction in marriage and forgiveness. On the other hand, McNulty (2008) found that in relationships in which one of the partners frequently behaved destructively, forgiveness is negatively correlated with satisfaction as forgiveness can encourage the misbehaving partner to not change his or her behavior.

1.1.3. NEURAL CORRELATES

Generally speaking, different brain areas seem to play a crucial role for forgiveness, including the prefrontal cortex (PFC) and the anterior cingulate cortex (ACC). To investigate the neural basis of forgiveness processes, Brüne, Juckel, and Enzi (2013) combined an ultimatum game and a dictator game. In the ultimatum game participants learned that there are fair and unfair opponents. In the dictator game, where these roles were reversed, the participants had the choice to forgive or to retaliate the unfair opponents. In said study, a higher activity in the right DLPFC was found when the participants were allocating a fair amount of money towards previously unfair opponents (=forgiveness). This specific correlation between the right DLPFC and forgiveness was confirmed by other studies with an adult and adolescent sample (Will, Crone, & Güroğlu, 2014; Will, Crone, Van Lier, & Güroğlu, 2016). Hayashi et al. (2010) found that the ventromedial PFC is correlated to the forgiveness of moral transgressions. In a connectivity analysis, Ricciardi et al. (2013) found significant correlations between the ACC, the DLPFC and the IFG. The ACC is inter alia a region associated with affect and emotion (Bush, Luu, & Posner, 2000) and the DLPFC is a region which is classically associated with cognitive control (MacDonald, Cohen, Stenger, & Carter, 2000; Yanagisawa et al., 2010). The IFG as part of the PFC is associated with cognitive and emotional empathy (Shamay-Tsoory, Aharon-Peretz, & Perry, 2009). Confirming these results, Strang, Utikal, Fischbacher, Weber, and Falk (2014) found a correlation between the IFG and forgiveness and explain this result with the need for empathy for forgiveness processes. Although there is considerable evidence for the involvement of especially the PFC in forgiveness processes, contradictory results were also found. Johnstone et al. (2015), for example, found a negative correlation between frontal lobe activity and forgiveness behavior. The authors explain this contrary finding with the following theory; a decreased frontal lobe functioning is associated with a decreased attention which leads to less rumination about the feeling to be wronged.

On a more conceptual level, there are, as of now, no broadly accepted neural models of how forgiveness exactly works. In one of the very few works on this topic, Clark (2005) describes in a theoretical paper how forgiveness could possibly work on a neural level. According to this model, in a first step, there are recurrent patterns of thoughts and anger. In this step especially the amygdala (related to fear) and the hippocampus (related to the hurtful memories) are relevant. In this conflict situation the sympathetic nervous system is activated for potential fight or flight reactions. This activation leads to increased emotional arousal and this increased arousal can lead to a reinforcement of the memory of the experienced victimization. As a next step, Clark (2005) proposes the interruption of these patterns. To this end, the cortex has to control the amygdala. This proposition aligns well with the above illustrated forgiveness definition of Wilkowski et al. (2010). If an interruption of negative emotions was successful, as a next step, Clark (2005) proposes that the victim should cognitively recognize that he/she has good reasons to forgive (e.g. good memories from the time before the experienced violation). This goes along with the phenomenon of the inhibition of the negative emotions – physically, there is a relaxation detectable as the fight or flight activity of the sympathetic nervous system gets reduced. In a last step, other, non-offending memories, should be more salient than the offending memories. As such, the amygdala is no longer activated by these negative memories.

1.2. COGNITIVE CONTROL

1.2.1. DEFINITION

Cognitive control is the summary of a specific set of mental processes which are essential for adapting behavior depending on the current goals of an individual (Inzlicht, Bartholow, & Hirsh, 2015). According to the literature there are three basic subfunctions of cognitive control: updating, shifting and inhibition (Miyake et al., 2000). Miyake et al. (2000) describe updating as the ability to replace old and no longer relevant information with new, currently relevant information. To this end, the cognitive control system codes incoming information for relevance depending on the present task. It is important to note that this is an active process which goes further than simple storage of information. Shifting describes the capability to switch back and forth between different operations, mental sets or tasks (Monsell, 1996). Beyond that, shifting also includes an active overcoming of a priming or interference of previous tasks. This specific process comes along with temporal costs especially when the shift is motivated internally and not caused by external cues (Miyake et al., 2000). Inhibition, as a subfunction of cognitive control, is defined as the ability to inhibit prepotent or automatic responses (Miyake et al., 2000). A classical task for investigating the ability to inhibit prepotent or automatic responses is the Stroop task (Stroop, 1935), in which the automatic, prepotent responses in incongruent trials have to be inhibited. According to the forgiveness definition of Wilkowski et al. (2010), the subfunction inhibition is the most relevant function of cognitive control for forgiveness processes.

1.2.2. RELEVANCE

“Cognitive control, in short, promotes the good life.” (p. 1; Inzlicht et al., 2015) – This quote illustrates the high relevance of cognitive control for nearly all areas of life. Hirsh and Inzlicht (2010) found a positive correlation between cognitive control outcomes and academic success. In other studies, over half of the variability in mathematic grades was explained by cognitive control (Visu-Petra, Cheie, Benga, & Miclea, 2011). Related to these findings, cognitive control is also positively correlated to financial well-being in the adult life (Drever et al., 2015). In a longitudinal study, Moffitt et al. (2011) found a high correlation between self-control (a concept which has a large overlap to cognitive control) and general physical health and criminal offending outcomes. Also, various (mental) diseases are highly correlated with a lack of cognitive control. Especially in ADHD (Barth et al., 2015; King, Colla, Brass, Heuser, & von Cramon, 2007) and addiction (Baler & Volkow, 2006; Kroczek, Haeussinger, Fallgatter, Batra, & Ehlis, 2017) but also in other problematic areas such as adiposity (Kamijo et al., 2012) this relation is also salient. Moreover, for the suppression of rumination, which is highly correlated to depression, the cognitive control network plays a crucial role (Rosenbaum, Hilsendegen, et al., 2018; Rosenbaum, Maier, et al., 2018).

1.2.3. NEURAL CORRELATES

The conflict-monitoring theory of Carter and Van Veen (2007) proposes different brain regions which are involved in cognitive control processes. Potential conflict situations are monitored by an internal monitoring system located in the ACC (e.g. Botvinick, Nystrom, Fissell, Carter, & Cohen, 1999; Kerns et al., 2004; MacDonald et al., 2000). If the ACC detects a conflict situation, this is signaled to the cognitive control system, which in turn initiates adaptive measures with the aim of achieving the internally defined action goals. The regulative device itself is assumed to be located in the DLPFC (Durston et al., 2003; Egner & Hirsch, 2005b; Milham, Banich, & Barad, 2003). Regarding the exact mechanisms underlying cognitive control, it is assumed that the DLPFC is able to amplify task relevant information (Egner & Hirsch, 2005a) when necessary. Wolkenstein and Plewnia (2013) showed a better cognitive control performance after increasing the activity in the left DLPFC via anodal tDCS in healthy and depressed participants.

1.3. CONCEPTUAL OVERLAP BETWEEN FORGIVENESS AND COGNITIVE CONTROL

Between forgiveness and cognitive control there is a theoretical as well as a neuronal overlap. Wilkowski et al. (2010) define forgiveness as a two-step process (both steps merge fluently); first, the decision to forgive the provocateur and second, the inhibition of baser, revenge seeking feelings. For the inhibition of these revenge seeking, baser emotions, cognitive control – and, more specifically – the subfunction of inhibition is necessary. This theoretical overlap is also mirrored in literature about the neural activation during forgiveness and cognitive control processes. In both processes, the ACC and especially the DLPFC play a crucial role.

In a seminal work, Pronk, Karremans, Overbeek, Vermulst, and Wigboldus (2010) investigated specifically the connection between cognitive control and forgiveness. They propose the importance of cognitive control abilities in general to successfully maintain relationships. More specifically, the following mechanism is hypothesized by the authors; cognitive control is known to be negatively related to rumination (e.g. Rosenbaum, Thomas, et al., 2018; Whitmer & Banich, 2010). However, rumination about experienced offenses and a focus on what happened can hinder forgiveness. Investigating the exact connection between cognitive control and forgiveness, Pronk et al. (2010) ran various experiments. In a first study, they found a positive correlation between a 2-back task (which is a classical task for assessing working memory which is highly correlated to cognitive control (e.g. Owen, McMillan, Laird, & Bullmore, 2005)) and the Tendency to Forgive Scale (Brown, 2003). In a second study, the relationship between cognitive control and forgiveness was investigated over a time course of 5 weeks and in a specific real-life situation. To this end, participants who had recently experienced violation by a close person were invited and conducted the Extrinsic Affective Simon Task (De Houwer, 2003) for measuring their cognitive control abilities. In the subsequent five weeks, they were asked via online questionnaires about the amount of their forgiveness towards the provocateurs. In this longitudinal data, a positive correlation between cognitive control and forgiveness was shown. Participants with high cognitive control were able to forgive more and faster compared to participants with low cognitive control. In a third and fourth study they asked additionally for the severity of the violation. In a regression analysis, they found cognitive control as a predictor variable and severity as a moderator for the extent of forgiveness. In particular, very severe offenses were forgiven faster by participants with high cognitive control compared to participants with low cognitive control. Additionally, they found rumination as a mediator for cognitive control and forgiveness. The authors interpret this specific result with the mechanism that people with high cognitive control are able to down-regulate their rumination, which facilitates forgiveness. In sum, the authors interpret these results an indicator for the top-down control of negative, unforgiveness causing ruminations through cognitive control.

A slightly distinct aspect in the relationship between cognitive control and forgiveness is promoted by Wilkowski et al. (2010). Here, cognitive control is seen as an inhibitor of anger and aggression which leads to forgiveness. The cognitive control resources are limited and especially in hostile situations hard to recruit; therefore, the a priori cognitive control abilities of different individuals are relevant. Investigating the connection between cognitive control and forgiveness, Wilkowski et al. (2010) ran two studies. In a first study, they assessed the cognitive control abilities of the participants in hostile situations via a self-developed combination of hostile primes and a Flanker task (=hostility-primed cognitive control; Eriksen & Eriksen, 1974; Wilkowski & Robinson, 2008). In a second task, they used a competitive reaction time task (Taylor, 1967) where the participants were provoked via loud white noise – which was chosen by an opponent – and afterwards had the option to retaliate by also administering loud noise towards their opponents. Additionally, the forgiveness opportunity was manipulated (longer time since the provocation and win of the participant vs. directly after provocation). In this study, they found less aggression with forgiveness as a mediator in participants with high hostility-primed cognitive control in comparison to participants with low hostility-primed cognitive control. This effect was highly accentuated when the opportunity to forgive was high. In a second study, Wilkowski et al. (2010) investigated the influence of hostility-primed cognitive control on forgiveness in a more environmental setting. To this end, the hostility-primed cognitive control parameter and questionnaire data about real experienced victimizations and experienced anger were assessed and analyzed. Here, hostility-primed cognitive control predicted forgiveness in daily life and the following reduction of experienced anger. These results are interpreted by the authors as proof for the hypothesis that cognitive control enables forgiveness behavior through the reduction of anger and aggression. The importance of the emotional aspects of forgiveness is also highlighted by Lichtenfeld, Buechner, Maier, and Fernández-Capo (2015). In this study, the authors compared forgiveness processes in emotional vs. decisional forgiveness conditions. In the emotional forgiveness condition, the participants get the instruction to wish the offender positive feelings; in the decisional forgiveness condition the participants get the instruction to think about the offender as a human being. Transgressions which were forgiven in the emotional forgiveness condition led to a faster forgetting of the transgression and, with this, to a more sustainable forgiveness process.

1.4. INTERIM SUMMARY & RESEARCH QUESTIONS

As outlined above there are clear indicators for the need of cognitive control for the implementation of forgiveness behavior after a transgression. In both, forgiveness and cognitive control, similar brain areas seem to be involved and on a theoretical level there are clear indications for the connection between cognitive control and forgiveness (inhibition of rumination about the transgression and inhibition of revenge seeking emotions). However, the exact mechanisms remain unclear. With the combination of the ultimatum game and dictator game it is possible to give the participants the possibility to take revenge or to forgive previously unfair opponents (Brüne et al., 2013). In this set of studies this paradigm sequence is used in combination with TBS and fNIRS. TBS can increase or decrease the activation in the stimulated brain area and fNIRS allows conclusions about activation changes in the underlying brain areas. With this combination it is possible to (partly) investigate the basic neural mechanisms of forgiveness behavior. This is complemented with an additional study on the relation between cognitive control and the inhibition of unwanted emotions (as a highly relevant sub-process in forgiveness processes).

2. METHODS

2.1. PARADIGMS

2.1.1. ULTIMATUM GAME AND DICTATOR GAME (STUDY 1, 3 & 4)

A combination of an ultimatum game and a dictator game was used in study 1, 3 and 4. This paradigm combination was mainly adapted from Brüne et al. (2013). First, the participants played an ultimatum game; the game consisted of 40 trials, and every trial started with a picture and the name of the opponent of the current trial for 3 seconds, followed by a fixation cross for a jittered 2–3 seconds. After this, the opponent split up 10 Euros and the offer was presented to the participants for 4 seconds. During this time period the participant had to decide whether to accept or reject the offer. In case of a rejection, neither of the two gamers received (virtual) money on this trial. Every trial ended with the display of how much money the participant and the opponent received in the current trial. In this game, which lasts about 8 minutes, the participants implicitly learned that there are 2 fair opponents (1 male, 1 female, offers between 3 and 5 Euros) and two unfair opponents (1 male, 1 female, offers between 0 and 2 Euro). An exemplary trial is depicted in Figure 1.

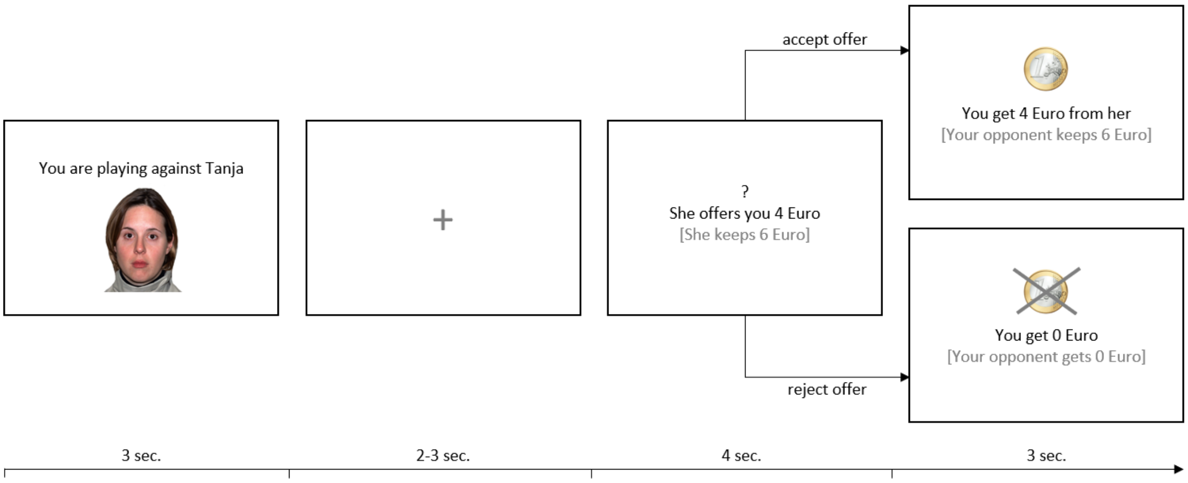

Figure 1: Exemplary trial of the ultimatum game against a fair opponent (figure modified from Brüne et al. (2013)).

After the implicit learning of which opponent was fair and which one was unfair, the participants played a dictator game with reversed roles. In this game, the participants played against the same opponents as in the previously played ultimatum game, but now the participants had to split up (virtual) 10 Euro in each trial. Every round started with the name and a picture of the current opponent for 3 seconds, which was followed by a fixation cross for a jittered 2–3 seconds and an input screen for 4 seconds in which the participant had to enter the amount of money which the opponent should receive. This screen was followed by a display of how much money the participant and the opponent received in the current trial for 3 seconds. It is important to note that the opponent in this game had no chance to reject an offer. This means that the participant was able to allocate any amount of money without fear of rejection. The whole game took approximately 8 minutes. In figure 2, one exemplary trial of the dictator game is depicted.

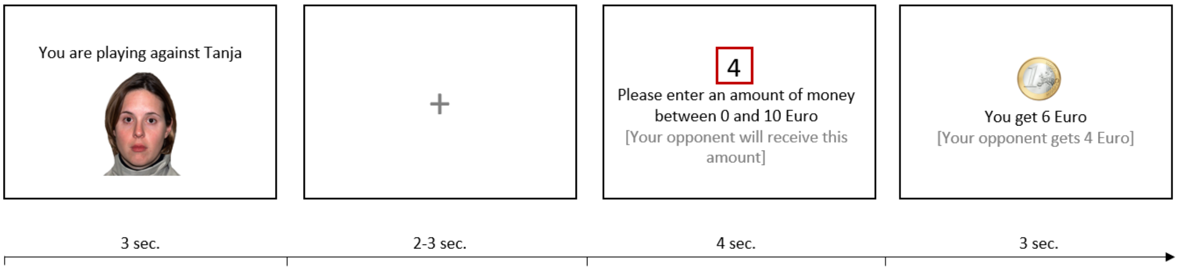

Figure 2: Exemplary trial in the dictator game (figure modified from Brüne et al. (2013)).

2.1.2. EMOTION REGULATION PARADIGM (STUDY 2)

The emotion regulation paradigm was mainly adapted from a study from Möbius et al. (2017). The participants had to watch a 4 minute movie clip from the movie Sophie's Choice (Pakula, 2007) with the instruction to allow or to suppress all upcoming feelings. The wordings of the preceding instructions were partly taken from Gross (1998) and Hayes et al. (2010) and translated into German for this study. The scene features a sadistic concentration camp supervisor who forces a mother to decide which of their two children has to be killed. The scene is highly dramatic and emotion inducing (cf. Möbius et al., 2017).

2.2. FUNCTIONAL NEAR-INFRARED SPECTROSCOPY (FNIRS)

With fNIRS it is possible to assess neural activation of the participants in a relaxed sitting position without head fixation and side effects and no noise during the measurement, which increases the ecological validity. Due to the relative transparency of biological tissue like skin, bones and cerebrospinal fluid for near-infrared light and the different absorption spectra for oxygenated (O_2Hb) and deoxygenated (HHb) haemoglobin, it is possible to measure cortical activation through the intact skull. An increase in the concentration of O_2Hb and a decrease of HHb indicates cortical activation within the specific underlying brain area. FNIRS was used in all studies of this thesis; in study 1 and 4 the effects of the TBS were assessed via fNIRS, in study 2 connectivity measurements were run during the presentation of an emotion inducing movie scene and in study 3 cortical activity during the dictator game was compared between groups using fNIRS. In all studies a commercial multi-channel NIRS system (ETG-4000 Optical Topography System; Hitachi Medical Co., Japan) with a temporal resolution of 10 Hz and a 3×11 probeset with 52 channels (16 detectors and 17 emitters with an inter-optode distance of 3 cm) was used. The placement of the probeset was based on the international 10–20 system for electrode placement (Jasper, 1958). The central optode of the bottom row was placed on Fpz and the probeset was symmetrically oriented towards T3/T4 (left/right hemisphere). The placement of the probeset is depicted in figure 3. The analyses of the fNIRS data is described in each manuscript.

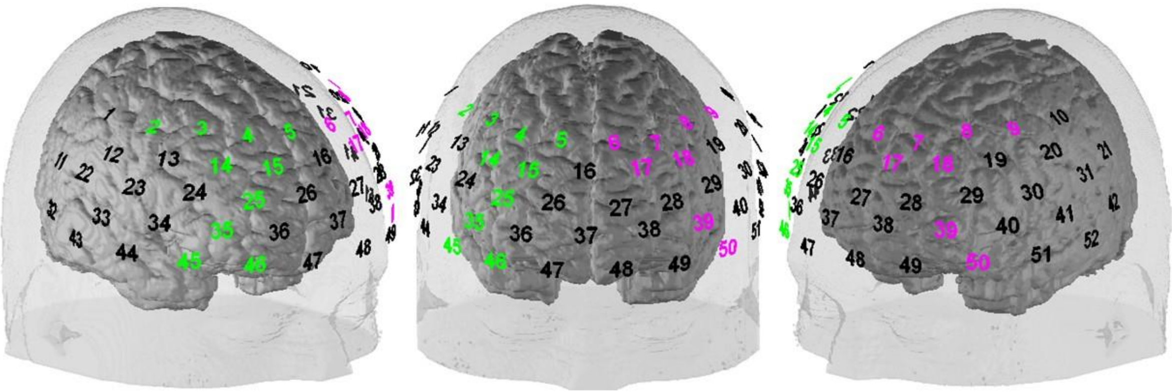

Figure 3: The numbers indicate the different channels. The colored numbers indicate the DLPFC, the main region of interest, the green numbers the right DLPFC, the pink numbers the left DLPFC.

2.3. THETA BURST STIMULATION (TBS)

In study 1 and 4 a TBS was applied. With TBS it is possible to directly test neurobiological hypotheses in a causal way. The TBS was applied in a within-participants design; the measurements were in a course of two weeks and double blinded and the order of the placebo- and verum stimulation was balanced. The effects of the TBS last up to 60 minutes after a stimulation duration of only 40 seconds with the inhibitory protocol and 190 seconds in the excitatory protocol (Huang, Edwards, Rounis, Bhatia, & Rothwell, 2005). Due to the application before the experiment, no distracting noise or feelings are noticeable during the experiment. The stimulation was applied over the right DLPFC (TMS coil located at electrode position F4 according to Herwig, Satrapi, and Schönfeldt-Lecuona (2003)). For the placebo stimulation, a placebo coil with electrodes placed close to the target region at the right DLPFC was used which involved the stimulation of skin afferences comparable to the real stimulation. The right DLPFC was chosen based on the results of Brüne et al. (2013) where the right DLPFC was highly activated in trials where participants showed forgiveness behavior. The TBS consisted of repeated three 50 Hz pulses at 80% of the individual resting motor threshold which was individually assessed before every stimulation. In study 1, a continuous TBS was applied; in this study, the bursts were given continuously for 40 seconds (600 pulses in total) inducing inhibition (Huang et al., 2005). In study 4, the activating intermittent TBS was applied; here, 2 seconds of stimulation were applied, repeated every 10 seconds with a total stimulation of 190 seconds (600 pulses altogether). For all stimulations an active-passive placebo/verum coil system by MagVenture® was used.

2.4. ELECTROMYOGRAPHY (EMG)

EMG was only used in study 2; therefore, it is described very briefly in this section. The EMG was applied over the Corrugator Supercilii; muscle contraction in this region is known as an indicator for negative emotions (Cacioppo, Petty, Losch, & Kim, 1986; Lang, Greenwald, Bradley, & Hamm, 1993). The EMG was recorded with a BrainAmpExG MR16 channel system amplifier with two electrodes over the left Corrugator Supercilii. For correcting the EMG data, vertical and orthogonal electrooculography was applied; Fz (Jasper, 1958) was used as ground.

2.5. PARTICIPANTS

In total 116 persons participated in 222 measurements sessions across all four studies. In study 1, healthy participants participated in two measurement sessions per participant (within-participants design; verum cTBS vs. placebo cTBS); in study 2 and 3, the same highly and low impulsive participants were compared (between-participants design) and in study 4 the highly impulsive participants participated in two measurement sessions per participant (within-participants design; verum iTBS vs. placebo iTBS). The categorization of the participants as low or highly impulsive was made based on the impulsivity scale of the Adult ADHD Self-Report Scale Symptom Checklist (Kessler et al., 2005).

3. STUDIES (OVERVIEW & CONTEXTUALIZATION)

3.1. STUDY 1

Title: Forgiveness and cognitive control – Provoking revenge via theta-burst-stimulation of the DLPFC.

3.1.1. RATIONAL

As outlined above, there is a high conceptual overlap between cognitive control and forgiveness. The DLPFC is considered a cognitive control area (e.g. Durston et al., 2003) where regulative control emerges whenever conflict has been detected. Brüne et al. (2013) found a higher activation in the right DLPFC in situations where the participants forgave their opponents. However, to our knowledge all studies in this field were of correlational nature so far; therefore, we applied inhibitory TBS over the right DLPFC for testing in a causal manner the following hypothesis:

H1: *The right DLPFC, as a cognitive control region, is essentially involved in forgiveness processes.*

For testing this hypothesis, the participants played the above outlined ultimatum game / dictator game combination where they had the possibility to forgive previously unfair opponents or to take revenge. This was combined with inhibitory TBS in two double-blinded and randomized placebo/verum stimulations in a within-participants design.

3.1.2. RESULTS

The participants were significantly less forgiving/more revenge seeking towards the previously unfair opponents after the verum stimulation (compared to the placebo stimulation). The fNIRS analysis confirmed the effect of the inhibitory TBS with less activation in channel 25 in the right DLPFC in trials where the participants allocated a fair amount of money to previously unfair opponents.

3.1.3. INTERIM DISCUSSION

The results of this study confirm the hypothesis that the right DLPFC (as a cognitive control area) is involved in forgiveness processes for the first time in a causal way. Nevertheless, the specific mechanisms of how the cognitive control area in the right DLPFC is executing forgiveness behavior remain unclear. The explanation model depicted in figure 4 could explain the specific mechanisms during the forgiveness process in healthy participants.

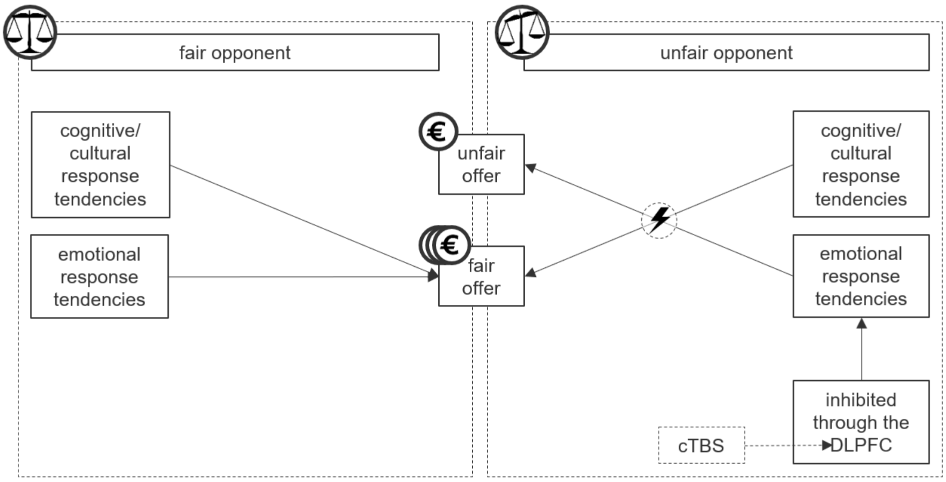

Figure 4: Model how the DLPFC is involved in forgiveness processes towards previously unfair opponents. The left side illustrates potential mechanisms in trials with fair opponents and the right side shows potential mechanisms towards unfair opponents. The offers made by the participants are depicted in the middle of the figure (unfair offer/fair offer).

In this model, developed on the basis of the literature and the results of study 1, there are different sources of response tendencies. On the one hand, we have cognitive/cultural response tendencies how to react to offending/unfair treatment. In the literature it is assumed that in most cases a forgiving (and not revenge seeking) behavior is desired from a cognitive/cultural perspective (e.g. Fish, 2008). On the other hand, we frequently experience transgressions and unfairness. In these cases we oftentimes have emotional response tendencies related to revenge seeking emotions such as anger or rage (cf. Crockett, Clark, Tabibnia, Lieberman, & Robbins, 2008; Mohiyeddini & Schmitt, 1997). In trials towards fair opponents, there are no negative emotions which could conflict with cognitive/cultural response tendencies. Towards unfair opponents, emotional and cognitive/cultural response tendencies conflict with one another. We propose that – with an intact DLPFC – it is easier to regulate these emotions and inhibit revenge seeking emotional response tendencies in trials towards unfair opponents.

3.2. STUDY 2

Title: To regulate or not to regulate: Emotion regulation in participants with low and high impulsivity

3.2.1. RATIONAL

Based on the explanatory model developed based on the results of study 1, in study 2 the relationship between forgiveness, emotion regulation of negative emotions and cognitive control was investigated with the aim to establish a broader empirical basis for the model outlined above. We proposed the following hypotheses:

H1: *Active emotion regulation (=suppression) comes along with significantly more connectivity in brain areas related to cognitive control.*

H2: *Participants with high cognitive control generally have lower expressions of negative emotions, whereas participants with low cognitive control need explicit instructions.*

In order to investigate the role of cognitive control in the regulation of negative emotions, a paradigm of Möbius et al. (2017) was adapted. Two groups were compared, participants with high impulsivity/low cognitive control and participants with low impulsivity/high cognitive control. The participants were presented with a negative emotion inducing movie scene and had either the instruction to allow all upcoming feelings or to suppress all upcoming feelings. The expression of negative emotionality was assessed via EMG over the eyebrow. Connectivity measurements were conducted in this study via fNIRS for investigating the involvement of cognitive control regions in regulating negative emotions. With this between-participants design, we were able to investigate the general responsiveness of participants with high vs. low cognitive control to negative emotion inducing material and we were able to compare the ability for emotion regulation depending on the extent of cognitive control.

3.2.2. RESULTS

For the condition *suppress all upcoming emotions*, we found a significantly higher connectivity between the left and the right DLPFC and the left DLPFC and the left and right frontopolar area across the groups. All these areas are part of the cognitive control network. Considering the EMG results, we found significantly less activation in the high cognitive control group (=main effect). This effect was especially accentuated in the condition *allow all upcoming emotions*; here, the responsiveness of the low cognitive control group to the negative emotion induction was particularly high.

3.2.3. INTERIM DISCUSSION

The results confirm the proposed hypotheses and are well in line with other findings in this field (cf. Ochsner, Silvers, & Buhle, 2012). The cognitive control network is involved in the regulation of negative emotions and the high cognitive control group is significantly better than the low cognitive control group, especially in implicit emotion control.

3.3. STUDY 3

Title: Disinhibited Revenge – an fNIRS Study on Forgiveness and Cognitive Control

3.3.1. RATIONAL

In study 1, the influence of an inhibited right DLPFC on forgiveness behavior was investigated and confirmed via neuromodulation. In study 2, the potential underlying explaining difference in emotion regulation abilities of participants with high- vs. low cognitive control was investigated. This study (study 3) has two aims: first, showing that not only an artificially reduced cognitive control is decreasing forgiveness behavior. Second, to investigate the underlying neural foundations of potential differences between high- and low cognitive control participants and potential links to emotional foundations of the behavior. Based on the literature and the previous studies the following hypotheses are proposed:

H1: *Participants with less cognitive control show less forgiveness behavior towards unfair opponents than participants with high cognitive control abilities.*

H2: *Less forgiveness behavior in the low cognitive control group is accompanied by less activity in the right DLPFC during forgiveness processes.*

H3: *These differences are based on the experience of more negative emotions of the participants with low cognitive control.*

In order to investigate the above outlined hypotheses, the participants played the ultimatum game and dictator game combination; during the dictator game the activity in the DLPFC was assessed via fNIRS. After the game, the participants were asked for the experienced revenge- and sympathy feelings towards the fair and unfair opponents.

3.3.2. RESULTS

In this study, participants with low cognitive control were more revenge seeking/less forgiving than participants with high cognitive control. In contrast to our hypothesis, these behavioral differences were not accompanied by higher cortical activation in the right DLPFC in the high cognitive control group which showed more forgiveness behavior. Surprisingly, in the left DLPFC a higher activation in low impulsive participants in trials towards unfair opponents was found. In a regression analysis it was found that in the high cognitive control group the sympathy towards the opponents was the only significant predictor of the dependent variable money allocation, whereas in the low cognitive control group revenge feelings towards the opponents were the only significant predictor of the dependent variable money allocation.

3.3.3. INTERIM DISCUSSION

On a behavioral level, we can confirm the results of study 1 and study 2; also a priori less cognitive control is associated with less forgiveness behavior. Surprisingly, in contrast to study 1 and the study of Brüne et al. (2013), this behavior was not associated with significantly less activation in the right DLPFC compared to the high cognitive control group which showed significantly more forgiveness behavior. The higher activation in the left DLPFC in trials with unfair opponents in the low cognitive control group is also very surprising. In some previous studies this higher activation in the left DLPFC was associated with revenge (Ricciardi et al., 2013; Strobel et al., 2011), even though the exact mechanisms remain unclear. Completely new aspects are the different predictors sympathy vs. revenge in the low vs. high cognitive control group. Maybe the experienced emotions in transgressional situations differ systematically depending on the extent of cognitive control.

3.4. STUDY 4

Title: The impact of TMS-enhanced cognitive control on forgiveness processes

3.4.1. RATIONAL

The fourth study was run as an extension of the results from study 1 and study 3. In study 1, less forgiveness behavior was measured after an inhibitory TBS of the right DLPFC. In study 3 we found less forgiveness behavior in participants with low cognitive control (which is generally associated with less activation in the DLPFC (e.g. Ehlis, Bähne, Jacob, Herrmann, & Fallgatter, 2008)). Based on these results we increased the activity in the right DLPFC via intermittent TBS and measured in a within-participants design participants with low cognitive control/high impulsivity scores. Again, the combination of an ultimatum and a dictator game was used for assessing the ability to forgive. Two issues were addressed: first, a vice versa testing of the results of the first study, and secondly the attempt to improve forgiveness behavior in a group which often fails to forgive with facilitating neuromodulation. Based on the results of the previous studies, the following hypotheses are proposed:

H1: *With an increased activity in the right DLPFC, the highly impulsive participants behave in accordance to common social norms.*

H2: *This is especially accentuated in more forgiveness behavior towards unfair opponents.*

3.4.2. RESULTS

With fNIRS, a higher activation in the right DLPFC was measured in the verum TBS condition compared to the placebo TBS condition, which means the activating intermittent TBS worked. Against the hypothesis, in the reactions toward previously unfair opponents no significant difference between the conditions (placebo vs. verum) was measured. Unexpectedly, towards previously fair opponents the participants were significantly more generous in the verum condition compared to the placebo condition.

3.4.3. INTERIM DISCUSSION

The results indicate that the increased activity in the right DLPFC helped the highly impulsive participants to inhibit their greed and to be more generous towards previously fair opponents. Whereas the ‘cold’ process of greed was influenced by neuromodulation, the ‘hot’ emotions caused in the transgression by the unfair opponents were not affected.

4. GENERAL DISCUSSION

In this set of studies, the relationship between forgiveness behavior and cognitive control was clarified partly. With cTBS of the right DLPFC it was possible to deduce a causal connection from the right DLPFC as a cognitive control region to forgiveness behavior. Based on study 1 it can be concluded that the right DLPFC is a key player for forgiveness behavior. In study 2 the involvement of the cognitive control network – and with this the right DLPFC – in emotion regulation was confirmed. In study 3 a difference between participants with high vs. low cognitive control in forgiveness behavior was measured. Surprisingly, these specific differences were not accompanied by higher brain activation in the right DLPFC. Instead, stronger activation was found in the left DLPFC in the less forgiving low cognitive control group. In previous studies, such an activation pattern of increased activity within the left DLPFC was associated with revenge feelings (Ricciardi et al., 2013; Strobel et al., 2011). In a fourth study the involvement of the right DLPFC in forgiveness processes was vice versa tested with activating TBS. Here, with an increased activity of the DLPFC, there was no decrease of revenge seeking behavior towards unfair opponents, but unexpectedly an increase of generosity towards fair opponents.

As outlined in the introduction, there are two options how cognitive control enables forgiveness processes. According to Pronk et al. (2010), cognitive control is needed for the inhibition of rumination about the offender and the transgression which could impede forgiveness. A different effect mechanism is seen by Wilkowski et al. (2010) who see cognitive control as a necessary resource for the inhibition of negative, revenge causing emotions. Based on the results of study 1, study 3 and the results of Brüne et al. (2013), it can be concluded that the relevant effect mechanism is more probably the inhibition of revenge inducing emotions. There is no break between the ultimatum game (=transgression) and the dictator game (=option for forgiveness vs. revenge) in the study of Brüne et al. (2013) and in study 1, study 3 and study 4, just a few minutes for applying the TBS and/or adjusting the fNIRS probeset. This could imply that in this paradigm combination there is not enough time to forget about the transgression vs. to ruminate about it. Additionally, after the whole dictator game in study 1 and study 4 (where TBS was applied) no differences in the sympathy, revenge and fairness ratings were measured between the conditions. This could be a first indication that with an intact or even more activated right DLPFC the process of forgetting about the transgression was no more 'successful' than with less activation in the right DLPFC. Moreover, in study 3 it was shown that different emotions towards the provocateurs seemed to play the crucial role for forgiveness behavior between participants with high vs. low cognitive control. Taken together, these findings seem to suggest that the most relevant effect mechanism underlying forgiveness behavior is the inhibition of negative, revenge causing emotions. For the investigation of the exact differentiation between the inhibition of emotion vs. rumination, more studies with additional rumination questionnaires and other self-report measures are needed.

4.1. FORGIVENESS MODEL

Based on the results of the studies of this thesis as well as previous findings, it is possible to develop a general forgiveness model. For the development of a more general psychophysiological forgiveness model the following findings of the present set of studies are relevant: the DLPFC as a cognitive control region plays a crucial role in forgiveness processes and enables forgiveness behavior (study 1); this causality is most probably – based on the findings of study 2 – that the cognitive control network (with the DLPFC as a key player) is involved in emotion regulation processes and that persons with low cognitive control experience higher emotionality compared to persons with high cognitive control. In study 3 the direct correlation between cognitive control and the ability to forgive was shown. Additionally, the importance of the underlying emotions in forgiveness processes and systematical differences between participants with high vs. low impulsivity confirm the crucial role of cognitive control in forgiveness processes. In a fourth study it was shown that an increased activity in the right DLPF does not lead automatically to more forgiveness behavior. Participants with increased activity in the right DLPFC were not more forgiving but they were more generous towards previously fair opponents.

Considering the important role of the DLPFC as a cognitive control region for forgiveness processes (which is especially highlighted by the results of study 1) another theory is important to note; the ‘conflict monitoring theory’ (Botvinick, Braver, Barch, Carter, & Cohen, 2001). According to this theory, conflict resolution is a process of two components (Botvinick et al., 2001; Botvinick, Cohen, & Carter, 2004; Carter & Van Veen, 2007). First, the monitoring and detecting of potential conflict situations by the ACC (Barch et al., 2001; Botvinick et al., 1999; Braver, Barch, Gray, Molfese, & Snyder, 2001; Kerns et al., 2004; MacDonald et al., 2000), which is supposed to be the internal monitoring system that is signaling the (apparent) existence of a response conflict to a cognitive control system. Second, this cognitive control system, which is located in the DLPFC, implements the cognitive control (Durston et al., 2003; Egner & Hirsch, 2005a; Kerns et al., 2004; Milham et al., 2003). The involvement of this cognitive control system (based in the DLPFC) in forgiveness behavior and prosocial reactions has been shown in various studies (Brüne et al., 2013; Knoch, Pascual-Leone, Meyer, Treyer, & Fehr, 2006; Maier et al., 2018; Makwana & Hare, 2012; Sanfey, Rilling, Aronson, Nystrom, & Cohen, 2003; Steinbeis, Bernhardt, & Singer, 2012; Wu, Zang, Yuan, & Tian, 2015).

In addition to our own results in study 2 where we found both, higher connectivity in the DLPFC during emotion regulation (compared to the no regulation condition) and a lower emotionality in the high cognitive control group, there are a lot of other findings in the literature which point in the same direction. In a meta-analysis, Kohn et al. (2014) show that in various different studies the DLPFC is involved in emotion regulation processes. Feeser, Prehn, Kazzer, Mungee, and Bajbouj (2014) showed how emotion regulation can be influenced via neuromodulation of the DLPFC. Participants were significantly better in up- or downregulating their feelings after receiving an anodal transcranial direct current stimulation compared to a placebo stimulation. Etkin, Büchel, and Gross (2015) specified the role of the DLPFC (in combination with other brain areas) in emotion regulation processes as conscious decision if a regulation is needed/wanted or not. In accordance with this, Etkin et al. (2015) highlighted the role of the DLPFC especially in explicit emotion regulation situations (contrary to implicit emotion regulation situations where the DLPFC does not seem to play an as important role). In the fourth study of this thesis, the results were not exactly as expected, here we expected after an activating iTBS of the DLPFC a better emotion regulation and because of this more forgiveness behavior. But unexpectedly the participants were more generous towards previously fair opponents but not more forgiving towards previously unfair opponents. Cautiously interpreted it can be concluded that highly impulsive participants experience more greed, and this is hampered through the activating TBS of the right DLPFC, but only towards fair opponents. Towards unfair opponents, the negative emotions are so intense that neuromodulation had no effect. Based on these results of study 4 we hypothesize that especially “cold” traits like greed can be influenced. But if anger and other revenge inducing feelings are experienced too strong, a higher activation of the DLPFC has no effect.

Generally, there are two reasons why a person could decide to regulate their emotion to forgive a provocateur. One reason can be the hope to increase the probability of earning benefits in the future due to their pro-social behavior; even in one-shot games this motivation can occur. Another reason can be that most people show pro-social behavior which is based on robust social principles for being generous and fair to opponents (Fehr & Camerer, 2007). In any case, the cognitive control system plays an important role as both reasons to regulate emotions are processed here, potential extrinsic incentives and own social norms (Declerck, Boone, & Emonds, 2013).

In figure 5, the results of the different studies are summarized into one forgiveness model. According to the model, the processes differ in trials towards fair and unfair opponents. Generally, it is assumed that the behavior is influenced by cognitive/cultural response tendencies and emotional tendencies. These emotional tendencies are based on state and trait components. Trait components are defined in this model as relatively stable constructs like a sense for fairness or greed. State components are rather defined as current feelings like anger or hate. According to the model, the response tendencies differ depending on the opponent. In trials with a fair opponent, healthy participants have the cultural and the emotional tendency to act fair. This differs in specific groups, for example in highly impulsive participants. Here, the cultural response tendency to allocate a fair amount of money plays a role. Highly impulsive participants have been shown to be rather greedy (Seuntjens, Zeelenberg, Van de Ven, & Breugelmans, 2015), so that there can be – in this specific group – an internal conflict between cultural and emotional response tendencies. In trials with unfair opponents, an even stronger internal conflict is observable. On the one hand, forgiveness as a pro-social behavior is desired from a cultural point of view (Fehr & Fischbacher, 2004). On the other hand, the transgression by the unfair opponent leads to negative emotions in both categories (state = revenge feelings, trait = sense of justice; cf. questionnaire outcomes studies 1,3 & 4) and with this to revenge seeking emotional response tendencies (Civai, 2013). These contrary tendencies can lead to an internal conflict. In this model it is proposed that with sufficient cognitive control it is possible to inhibit these revenge seeking emotions up to a certain amount. But based on the results of study 4, where an activating TBS of the right DLPFC was not able to increase the probability to forgive, this hypothesis has to be limited. When the experienced emotions are too strong (as it is in certain groups, see e.g. the group comparison in study 3), the DLPFC is not able anymore to adequately inhibit revenge seeking feelings.

Additionally to differences regarding the quantity and quality of the experienced emotions (cf. study 3) and the a priori amount of cognitive control abilities (cf. study 2), there is a large influence of the cultural and social background as well as the relationship to the provocateur (Karremans et al., 2011).

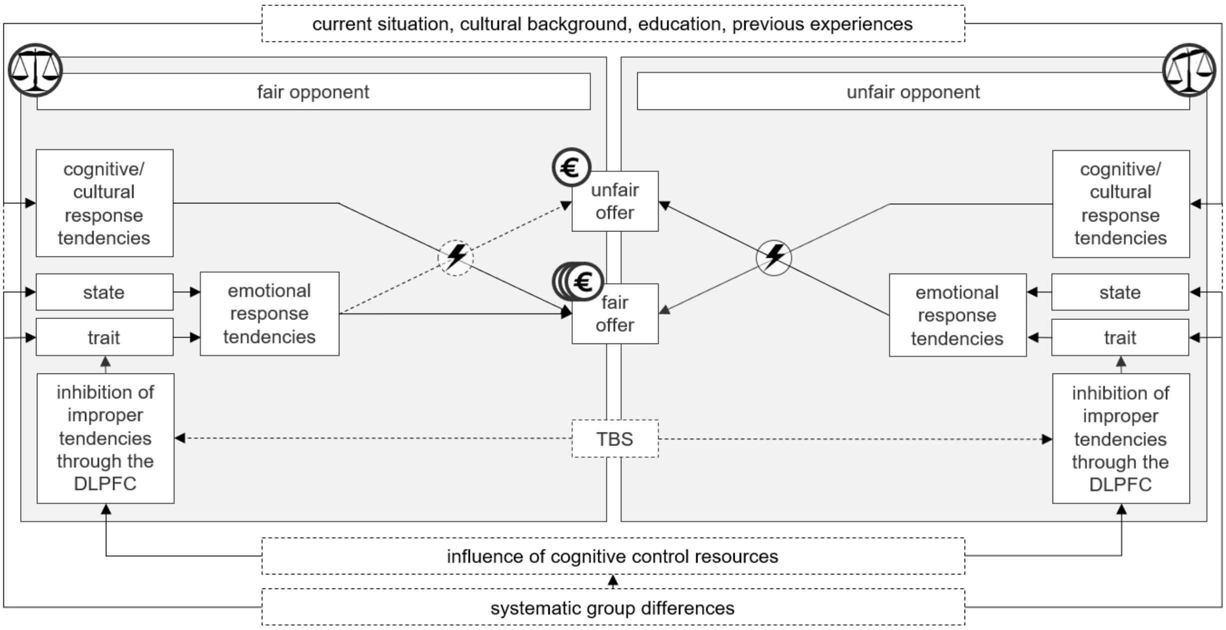

Figure 5: Schematic depiction of the various influencing factors which can lead to forgiveness or revenge. According to the model it is proposed that our behavior is influenced by external factors like the current situation, the cultural background, the educational background and previous experiences. Additionally, the behavior is influenced by internal factors like cognitive control resources and experienced emotions. The resultant emotional response tendencies are in this model separated in state emotionality like anger and trait emotionality like greed.

4.2. LIMITATIONS & OUTLOOK

The present set of studies provides new insights in forgiveness processes but also comes along with various limitations. In all studies mainly young, female university students were measured. In terms of a greater generalizability, in future studies participants from different ages, sex and educational levels should be measured. In various previous studies it was shown that it is harder for men to forgive than for women (Shackelford, Buss, & Bennett, 2002; Wade & Goldman, 2006) although there are contrary results (Miller & Worthington Jr, 2010). Whereas Toussaint and Webb (2005) found differences in the empathy towards offenders but no differences in forgiveness, Miller and Worthington Jr (2010) found more forgiveness behavior in women. But even when there are no significant differences in forgiveness behavior there seem to be different factors which influence forgiveness behavior in men and women. In women guilt-proneness, anger reduction and detachment are relevant, in men age, shame-proneness and pride (Konstam, Chernoff, & Deveney, 2001). The open question remains, if these different foundations of forgiveness behavior would also be detectable in the brain activation over the right DLPFC during forgiveness processes and if these differences may differ in the malleability via neuromodulation. It could be hypothesized that these different foundations could lead to different activation patterns comparable to the different activations in the left DLPFC in study 3 which are presumably based on different foundations of forgiveness behavior. For analyzing these potential differences in future studies, enough men and women should be measured to run group comparisons.

Also, in this study mainly German university students were studied, but in previous studies cultural differences in gaming behavior were found, caused by different values and beliefs (Chuah, Hoffmann, Jones, & Williams, 2009). Particularly, the responses towards the offers differed significantly between different cultures (Chuah et al., 2009; Oosterbeek, Sloof, & Van De Kuilen, 2004). Also in more general terms, there seem to be fundamental differences in forgiveness processes especially between eastern and western cultures (Ho & Fung, 2011; Karremans et al., 2011). Different aspects are discussed: first, a different emotionality which could lead to different forgiveness outcomes (cf. Ho & Fung, 2011), and second, a stronger orientation on social norms for maintaining social harmony in collectivistic cultures such as Japan or China (cf. Karremans et al., 2011). A combination of the ultimatum game and the dictator game together with an assessment of the brain activity (e.g. with fNIRS) would make it possible to investigate the complex underlying foundations for potential different forgiveness behavior. According to the results in study 3, a greater desire for revenge (= more emotionality) should come along with a higher brain activation in the left DLPFC in dictator game trials towards unfair opponents. Studying these differences could help to understand how higher cognitive concepts like forgiveness are influenced by cultural norms and how these cultural norms are mirrored in brain activity.

The ultimatum/dictator game used in study 1, 3 and 4 had the advantage of very few confounding parameters, little time consumption and clear events during the game in which the neural activity was assessed. But this artificial paradigm combination also comes along with various limitations. There was no real relationship between the participants and the provocateurs. In our daily life, victimization happens often to persons who are closely related to the offender, for example romantic partners, siblings or colleagues. Towards these closer persons it can be assumed that forgiveness processes are much more complex (cf. Carr & Wang, 2012). Additionally, it is also known that forgiveness processes can need some more time (weeks, months or even years; e.g. Pronk et al., 2010; Sells & Hargrave, 1998) than the participants had in the paradigm combination of this study set (time between transgression and possibility to forgive: approximately 7 minutes). Also, the ecological validity of the paradigms is low, even though the participants were instructed to act like they would play for real money and against real opponents it was obvious that they were just playing against an algorithm. But even if the ecological validity is low, the experiences in the (virtual) dictator game seem to affect the real life significantly (Franzen & Pointner, 2013). Furthermore, it can be discussed if, with the paradigms at hand, real forgiveness behavior was investigated. Alternatively, it could be argued that in these games only simple tit-for-tat mechanisms had an effect. Moreover, the participant could have educational approaches with allocating unfair amounts of money towards unfair opponents without having revenge related intensions. For all these reasons, several adaptions of the paradigms could increase the ecological validity. The motivation could be increased with linking the actual financial compensation of the participants to their behavior in the games. Another idea could be to invite couples for playing the games against each other where it would be, however, difficult to manipulate the offers.

Another potential limitation is the slightly unclear effect of TBS in prefrontal brain areas. The used TBS-protocol of Huang et al. (2005) was developed and reviewed for the motor areal of the brain and in this region it induces consistent inhibition/activation. In the DLPFC, where the TBS was applied in study 1 and 4, the results are less consistent (Grossheinrich et al., 2009; Woźniak-Kwaśniewska, Szekely, Aussedat, Bougerol, & David, 2014). But for targeting this caveat, the inhibitory and excitatory effect of the TBS over the right DLPFC was assessed successfully with fNIRS. These results confirm also findings of other studies in which the DLPFC was stimulated successfully via TBS (e.g. Chung, Rogasch, Hoy, & Fitzgerald, 2018; Tupak et al., 2013).

The results especially of study 1 and study 3 underline the importance of cognitive control for forgiveness behavior. In a seminal study, Barnea-Goraly et al. (2005) showed impressively how the white matter of the right DLPFC develops over the age from 6 to 20 years. The amount of white matter in the right DLPFC is increasing linear to the age of the children/adolescents. In a review, Blakemore and Choudhury (2006) also describe an increasing performance in classical cognitive control tasks measuring inhibitory control, processing speed, working memory and decision making. Here the question arises, if this better performance in cognitive control tasks also comes along with a higher probability to forgive an offender. Girard and Mullet (1997) compared the propensity to forgive in different age groups but they did not use any brain activity measurements or cognitive control tasks to contextualize age specific differences in the propensity to forgive. But like expected, keeping the results of Barnea-Goraly et al. (2005) in mind, the propensity to forgive increased from adolescent to old. The youngest population investigated by Girard and Mullet (1997) was 15 years old; in future studies it could be highly interesting how forgiveness behavior changes in the ultimatum game/dictator game combination starting in childhood up to adulthood. It could be investigated if forgiveness behavior is positively correlated to the white matter volume in the right DLPFC and other classical cognitive control tasks like the Stroop task.

Another aspect for future studies could be the investigation of forgiveness behavior of various clinical samples, which are known for insufficient emotion regulation and/or divergent social norms. In various mental disorders like borderline personality disorder, depression, substance-use disorders or somatoform disorder, deficient emotion regulation abilities play an important role in maintaining the disease (Berking & Wupperman, 2012). In borderline personality disorder especially, emotion dysregulation is a main symptom (Barnow et al., 2012). In this specific patient group, it would be interesting to see how forgiveness behavior and activation in the right vs. left DLPFC differ in comparison to a healthy control group. Additionally, it would be interesting to investigate the relevant factors for forgiveness behavior in a regression analysis for evaluating potentially different factors between participants with borderline personality disorder and healthy controls. With a study like this, two things could be evaluated: first, the interplay of cognitive processes and emotion regulation in borderline personality disorder patients and second, how participants with a lack of emotion regulation behave in the paradigm combination. With these, new insights in forgiveness processes could be provided.

In the present set of studies, fNIRS over the frontal lobe was used to assess the brain activity. Using this method, measurements with a good temporal resolution in a comparably natural environment and low preparational and financial effort were possible. Nevertheless, with fNIRS only the brain activation in cortical areas is measurable. According to the conflict monitoring theory, the ACC plays a crucial role (Botvinick et al., 2001; Botvinick et al., 2004; Carter & Van Veen, 2007) and especially for emotions the amygdala is a key player (Lindquist, Wager, Kober, Bliss-Moreau, & Barrett, 2012). The simultaneous measurement of activation changes in these brain areas would provide further insights in forgiveness processes and potential network influences of TBS.

4.3. CONCLUSION

It can be concluded that cognitive control is relevant for forgiveness processes in healthy participants, most probably with inhibiting revenge seeking emotions. Additionally, the experienced emotions and personal values seem to play an important role. Because of this, systematic differences in forgiveness processes between different subgroups are proposed.

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6. STATEMENTS OF CONTRIBUTION

STUDY 1

This study was designed by Moritz Maier, based on a previous study by Martin Brüne, Georg Juckel and Björn Enzi. The design was discussed with Ann-Christine Ehlis, Florian Häußinger and Martin Brüne. All measurements were run by Moritz Maier and research assistants (under supervision of Moritz Maier). The data correction and analyses were run by Moritz Maier and partly by David Rosenbaum under supervision of Ann-Christine Ehlis, Christian Plewnia and Florian Häußinger. The manuscript was written by Moritz Maier and reviewed and complemented by Ann-Christine Ehlis, Martin Brüne, David Rosenbaum, Florian Häußinger, Christian Plewnia and Andreas Fallgatter.

STUDY 2

This study was designed by Moritz Maier. The design was discussed with Ann-Christine Ehlis and Julian Schiel. All measurements were run by Moritz Maier, Julian Schiel and research assistants (under supervision of Moritz Maier). The data correction and analyses were run by Moritz Maier and partly by David Rosenbaum and Julian Schiel under supervision of Ann-Christine Ehlis. The first draft of the introduction was written by Julian Schiel and Moritz Maier. The other parts of the manuscript were written by Moritz Maier and reviewed and complemented by Ann-Christine Ehlis, Julian Schiel, David Rosenbaum, Martin Hautzinger and Andreas Fallgatter.

STUDY 3

This study was designed by Moritz Maier, based on a previous study by Martin Brüne, Georg Juckel and Björn Enzi. The design was discussed with Ann-Christine Ehlis. All measurements were run by Moritz Maier and research assistants (under supervision of Moritz Maier). The data correction and analyses were run by Moritz Maier and partly by David Rosenbaum under supervision of Ann-Christine Ehlis. The manuscript was written by Moritz Maier and reviewed and complemented by Ann-Christine Ehlis, Martin Brüne, David Rosenbaum and Andreas Fallgatter.

STUDY 4

This study was designed by Moritz Maier, based on a previous study by Martin Brüne, Georg Juckel and Björn Enzi. The design was discussed with Ann-Christine Ehlis. All measurements were run by Moritz Maier and research assistants (under supervision of Moritz Maier). The data correction and analyses were run by Moritz Maier and partly by David Rosenbaum under supervision of Ann-Christine Ehlis. The manuscript was written by Moritz Maier and reviewed and complemented by Ann-Christine Ehlis, Martin Brüne, David Rosenbaum and Andreas Fallgatter.

7. STUDIES

7.1. STUDY 1: WHAT DOES IT TAKE TO FORGIVE - PROVOKING REVENGE VIA THETA-BURST-STIMULATION OF THE DLPFC

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Published in NeuroImage 183 (2018) 769–775

Abstract

In order to act in a socially acceptable way, the ability to forgive is indispensable. It has been suggested that forgiveness relies on cognitive control, more specifically inhibition. In this study, we combined an ultimatum game (UG) and a dictator game (DG) with inhibitory, continuous theta-burst stimulation (cTBS; verum vs. placebo, within-subjects design) of the right dorsolateral prefrontal cortex (DLPFC) to investigate the effect of reduced cognitive control on forgiveness. The cTBS effects were controlled with functional near-infrared spectroscopy. To this end, participants played an UG against fair and unfair opponents, where they had to accept or reject (fair and unfair) monetary offers, and then received a cTBS prior to playing a DG against the same opponents with reversed roles. The participants now had the possibility to forgive the unfair opponents (allocation of a fair amount of money) or to take revenge. Following verum cTBS, participants allocated significantly less money to their unfair opponents than in the placebo cTBS condition. Also, reaction times (RTs) differed significantly between verum and placebo cTBS for unfair opponents (higher RTs following verum stimulation) but not for fair opponents. These results strongly indicate that cognitive control is a fundamental requirement for overcoming unwanted emotional responses.

Keywords: *Cognitive Control, DLPFC, fNIRS, Forgiveness, TMS, Revenge*

Introduction

Forgiveness is a universal construct of cultural and religious value for nearly all communities and religions (McCullough, Bono, & Root, 2005). In both monotheistic (e.g. Stein, 2009) and indigenous religions (e.g. Basden, 1966; De Laguna, 1972), the draconian “Talion principle” is socially sanctioned whereas forgiveness is socially desired (Fish, 2008). Depending on the situation, however, it can sometimes be difficult to follow principles of altruistic, fair and cooperative behavior (DeWall, Baumeister, Stillman, & Gailliot, 2007; Fehr & Fischbacher, 2004a), which is particularly hampered when the counterpart acts in an unfair or uncooperative manner. In such cases, our behavior is oftentimes strongly influenced by emotions such as anger or frustration (Civai, 2013), and cognitive control is needed to continue acting in a socially acceptable way (e.g. Pronk et al., 2010; Wilkowski et al., 2010). Conceptually, cognitive control consists of three major neuropsychological sub-functions, namely inhibition, task-switching and updating (Miyake et al., 2000). Forgiveness, on the other hand, comprises two processes which merge fluently: first, the decision to forgive the provocateur; and second, the inhibition of the desire for revenge (Wilkowski et al., 2010). Therefore, inhibition is discussed as a fundamental, top-down requirement for acting cooperatively in social situations involving cognitive (response) conflict (Pronk et al., 2010), suggesting a theoretical overlap between both constructs.

According to a prominent theory on cognitive control (“conflict-monitoring theory”, “conflict-control-loop"; M. Botvinick, T. Braver, D. Barch, C. Carter, & J. Cohen, 2001; M. Botvinick, J. Cohen, & C. Carter, 2004a; Carter & Van Veen, 2007), the resolution of response conflict is accomplished by an executive control system through: (1) monitoring of conflict situations by an internal monitoring system signaling the occurrence of response conflict to a cognitive control system, which in turn (2) initiates adaptive measures to overcome the conflict situation. Neuroanatomically, medial prefrontal areas including the anterior cingulate cortex (ACC) have been suggested to play a central role in conflict monitoring and detection (e.g. Barch et al., 2001; Botvinick et al., 1999; Braver et al., 2001; Carter et al., 2000; Durston et al., 2003; Kerns et al., 2004; MacDonald et al., 2000), whereas the dorsolateral prefrontal cortex (DLPFC) seems to be involved in the subsequent implementation of cognitive control (Durston et al., 2003; Egner & Hirsch, 2005a; Kerns et al., 2004; MacDonald et al., 2000; M. P. Milham et al., 2001; Milham et al., 2003). In line with this model as well as the assumed role of cognitive control for forgiveness behavior, prosocial reactions towards unfair opponents have previously been shown to crucially depend on activation within the right DLPFC (e.g., Brüne et al., 2013; Knoch et al., 2006; Sanfey et al., 2003; Wu, Zang, Yuan, & Tian, 2015b).

In more detail, Brüne et al. (2013) had participants first perform an ultimatum game (UG) with (virtual) opponents who distributed a total amount of 10 Euro per trial in an either fair (offers between 3 and 5 Euro) or unfair manner (offers between 0 and 2 Euro) (these offers could then either be accepted or rejected by the participants whereby, in the latter case, nobody received anything). After this learning experience, the roles were reversed for the second part of the experiment, where the participants now had the chance to split up 10 Euro per trial between themselves and the same opponents they had gotten to know before. In this part of the experiment, there was no possibility for the opponents to reject an offer, so it was – by definition – a dictator game (DG). It is important to note that there is a small but relevant difference between the UG and the DG considering the possible response opportunities of the acceptor. While in the UG the acceptor can punish the distributor by not accepting the offer, in the DG the acceptor is completely passive. This difference makes it even easier to retaliate against unfair opponents in the DG. An increased DLPFC activation during trials in which participants allocated a fair amount of money to a previously unfair opponent ("forgiveness" condition) strongly indicates an involvement of the prefrontal control system in this high-conflict situation (Brüne et al., 2013); nevertheless, these findings are – as many others in this field of research – merely correlational.

In order to obtain stronger, causal evidence for the important role of the cognitive control system (i.e., the DLPFC) for forgiveness behavior, we adopted the experiment from Brüne et al. (2013)and combined it with an inhibitory (continuous) theta-burst stimulation protocol (cTBS; Huang et al., 2005). Repetitive transcranial magnetic stimulation (rTMS) can lead to inhibition or facilitation of neural pathways in underlying cortical areas (Wassermann & Lisanby, 2001), and theta-burst rTMS shows effects lasting up to 60 minutes after less than 5 minutes of stimulation (Huang et al., 2005). Previously, Knoch et al. (2006)) demonstrated the impact of rTMS on acceptance rates in an UG; however, until now, the effects of inhibitory (or facilitating) brain stimulation on 'forgiveness' – i.e. interactions of fair (vs. unfair) monetary offers with fair vs. unfair opponents – has never been investigated. Following inhibitory cTBS of the right DLPFC, we expect more revenge behavior (i.e., unfair offers) towards previously unfair opponents (as compared to placebo stimulation) because of the gap between more revenge-seeking, emotion-driven action tendencies and forgiveness-affirming cultural norms in this case, where the (inhibited) right DPLFC is no longer able to adequately suppress the desire for revenge. Acting according to cultural norms – even towards people who have previously harmed us (i.e., forgiveness behavior) – requires cognitive control (especially inhibition); if we are not able to recruit cognitive control capacities (in the present study hampered through cTBS), we tend to show more emotion-driven behavior. For fair opponents, we expect no differences between cTBS and placebo stimulation because, in this case, cultural norms and emotion-driven action tendencies should usually concur, and inhibition of culturally inappropriate emotion-driven behavior (i.e., cognitive response control) would therefore not be needed. Moreover, we expect to directly observe the effect of cTBS in the form of lower activation patterns within the right DLPFC during performance of the described DG using online recordings of hemodynamic responses (via functional near-infrared spectroscopy), especially for the critical condition (fair offer made to previously unfair opponent).

Method

Test procedure

The present study followed a within-subject design, with two measurement sessions over the course of two weeks involving either a verum or sham (i.e., placebo) cTBS protocol. To avoid sequence effects, the order of sham and verum stimulation was balanced and implemented in a double-blind fashion.

Subjects

19 subjects aged between 19 and 31 years (*M*=23.63, *SD*=3.48) participated in this study. This sample size is based on an a priori power estimation and is derived from a calculation of the effect size of an inhibitory TBS challenge as reported by Tupak et al. (2013). This study involved a design similar to the one proposed here, as the effects of an inhibitory TBS challenge on prefrontal oxygenation as well as behavioral data were examined in a healthy group of subjects during functional NIRS. For right-hemispheric stimulation, the within-subject effect of the cTBS protocol (regarding task-related changes in cerebral oxygenation for the baseline vs. post-TBS measurement) reached an effect size f=0.40 (based on a partial η^2=0.139 as derived from the repeated-measures ANOVA; data obtained from the first author). Assuming a predefined p of .05 and a power criterion of at least 90%, this effect size corresponds to the measured sample size of n=19.

14 out of 19 participants were female, and all of them were students at the University of Tübingen. For their participation, they received a financial compensation of 10 Euro/hour which was unrelated to their behavior in the paradigm. No participant reported a history of psychiatric or neurological disorder and all of them were right-handed, native German speakers. The scores of the questionnaires used to assess different psychological variables (see also below) are shown in table 1.

Table 1: *Questionnaire scores of the study sample*

	Mean	SD	Range
BDI	5.68	6.71	0–22
ASRS	30.89	4.89	25–39
CFQ	77.05	14.86	54–112
Tendency to forgiveness Scale	14.68	3.77	7–20
Willingness to forgive Scale	21.36	3.66	14–27
ATQ	83.52	9.44	63–100

Beck Depression Inventory (BDI; Beck, Steer, & Brown, 1996b) , adult ADHD self-report scale (ASRS; Kessler et al., 2005), Cognitive Failure Questionnaire (CFQ; Lumb, 1995), Tendency to Forgiveness Scale (Brown, 2003), Willingness to forgive Scale (M Allemand, Sassing-Meng, Huber, & Schmitt, 2008), Adult Temperament Questionnaire (ATQ; Wiltink, Vogelsang, & Beutel, 2006)

Recruitment procedure

The participants were recruited via an online-platform for potential participants in Tübingen. Exclusion criteria were any contraindications for cTBS (see Rossi, Hallett, Rossini, Pascual-Leone, & Group, 2009), chronic or acute diseases which can influence the cerebral metabolism (moderate or severe craniocerebral trauma, kidney insufficiency, diabetes, unattended hypertension), neurological or psychiatric illnesses (present or past) or acute endangerment of self or others. The ethics committee of the Medical Faculty of the University of Tübingen approved this study, the implementation of which was in accordance with the current version of the Declaration of Helsinki. Written informed consent was obtained from the participants after detailed written and oral information about the study.

Paradigm

The paradigm was largely adapted from Brüne et al. (2013) and consisted of two different tasks, an UG and a DG. Both games comprised in total 40 trials, resulting in respective task durations of approximately 9 minutes each. For each trial of the UG, the participants first saw a picture of the opponent for 3 seconds. This was followed by a jittered 2–3 s anticipation period. After that, the offer of the opponents was presented for 3 seconds (amounts between 0 and 5 Euro were offered out of a total amount of 10 Euro per trial). During this decision period, the participants had to decide if they wanted to accept or reject the offer made by the opponent, which they indicated via button press (the arrangement of the buttons was balanced across participants). If the participant rejected the offer of the opponent, both received 0 Euros. At the end of each trial, a 3 s feedback screen informed the participants about the resulting amount of money for themselves and their opponent. The inter-trial interval varied between 2-3 s. Four different human characters were presented (two males, two females), whereby two of them (one male, one female) made consistently fair offers (between 3 and 5 Euro) and two of them made consistently unfair offers (between 0 and 2 Euro). The classification of fair and unfair offers was made based on previous literature (e.g., Brüne et al., 2013; Sanfey et al., 2003). The participants were not informed about the different allocation systems of the opponents. After performing the UG, the cTBS was applied (see below). In the following DG, the participants played against the previously introduced four human characters (two fair, two unfair). Now the roles were reversed and the participants themselves were asked to split up 10 Euro for each trial. The structure of the trials and all relevant time points were equivalent to the UG with the notable exception that offers could not be rejected by the opponents. In both games, the participants were instructed to imagine that they were playing with real persons and for real money. For presenting the experiment, the “Presentation” software-package (Neurobehavioral Systems Inc., Albany, CA, USA) was used.

Theta-burst stimulation

For the transcranial magnetic stimulation of the right DLPFC (TMS coil located at electrode position F4 according to Herwig et al. (Herwig et al., 2003); see Figure 1[C]), the very efficient theta-burst stimulation protocol (TBS; Huang et al., 2005; Huang & Rothwell, 2004) was used. In contrast to “classical” high- or low-frequency rTMS, which requires stimulation of at least 20 minutes, theta-burst rTMS shows similar effects, lasting up to 60 minutes, after less than 5 minutes of stimulation (Huang et al., 2005). The use of TBS followed the protocol developed by Huang et al. (Huang et al., 2005): 5 Hz theta bursts of three 50 Hz pulses at 80% individual resting motor threshold were repeatedly applied. These bursts were given continuously for 40 seconds (600 pulses total). The protocol induces consistent inhibition in the human motor cortex (Huang et al., 2005), but the reproducibility of the inhibitory effect in the DLPFC is less consistent (e.g. Grossheinrich et al., 2009; Woźniak-Kwaśniewska et al., 2014). Nevertheless, other studies seem to provide sufficient support for at least partial reproducibility of the inhibitory effect in other brain areas such as the DLPFC (e.g. Chung, Rogasch, Hoy, & Fitzgerald, 2018b; Tupak et al., 2013). In addition, the specific effects of the cTBS were controlled via fNIRS measurements in this study. All TBS sessions were applied in a double-blind fashion using an active-passive placebo/verum coil system by MagVenture®. The placebo sessions were masked via electrodes inducing a feeling comparable to the verum protocol at the stimulated head area. The DG began approximately 7 minutes after the end of the stimulation, which is the time it took to arrange the fNIRS cap and start the measurement and the paradigm.

Functional near-infrared spectroscopy

During the DG, cortical activation of the participants was measured with functional near-infrared spectroscopy (fNIRS). Since biological tissue (e.g., skin, bones, cerebrospinal fluid) is relatively transparent for near-infrared light, and oxygenated (O2Hb) and deoxygenated (HHb) haemoglobin absorb near-infrared light with different absorption spectra (A. Fallgatter, A. C. Ehlis, A. Wagener, T. Michel, & M. Herrmann, 2004; Haeussinger et al., 2011), fNIRS allows for a measurement of cortical activation through the intact skull. Thereby, an increase in the concentration of O2Hb and a decrease of HHb indicate cortical activation within a specific brain region. For this study, we used a commercial multi-channel NIRS system (ETG-4000 Optical Topography System; Hitachi Medical Co., Japan) with a temporal resolution of 10 Hz. A 3 × 11 probeset with 52 channels was used, comprising 16 detectors and 17 emitters with an inter-optode distance of 3 cm. Based on the international 10-20 system for electrode placement (Jasper, 1958b), the central optode of the bottom row was placed on Fpz and the probeset was symmetrically oriented towards T3/T4 (left/right hemisphere), respectively (again bottom row).

Questionnaires

In this study, different questionnaires were used to assess various psychological variables related to cognitive control and forgiveness. The questionnaires were completed online before starting the UG via Sosci Survey (D. J. Leiner, 2014). The following instruments were used: Beck Depression Inventory (BDI; Beck et al., 1996b), Cognitive Failure Questionnaire (CFQ; Lumb, 1995), Adult Temperament Questionnaire (ATQ; Wiltink et al., 2006), Tendency to Forgiveness Scale (Brown, 2003), adult ADHD self-report scale (ASRS; Kessler et al., 2005) and the Willingness to forgive Scale (M Allemand et al., 2008). Additionally, the fairness, desire for revenge and sympathy perception of the participants towards their opponents was assessed after the experiment. Also, at the end of the second session, the participants were asked to indicate which of the two sessions they thought involved verum or sham cTBS; both were again assessed with Sosci Survey (D. J. Leiner, 2014).

Statistical processing (Behavioral data)

In order to test the behavioral data for differences in the amount of money allocated by the participants in different conditions (fair vs. unfair opponent; placebo TBS vs. real TBS), we used a non-parametrical Permutation test since a repeated measurement ANOVA would have violated several statistical-mathematical assumptions (e.g., the assumption of normally distributed data). Regarding the number of unfair money allocations in the DG, we performed non-parametric permutation tests for repeated measurement data with 10000 random permutations on the frequencies of unfair money allocations in the verum vs. placebo condition separately for fair and unfair opponents (see e.g. Gibbons & Chakraborti, 2011). Unfair money allocations were defined as offers lower than three Euro (cf. Brüne et al., 2013). As described in the introduction, we hypothesized that inhibitory stimulation of the right DLPFC would influence the money allocation to unfair opponents, but not to fair opponents. Because the reaction times (RTs) were not normally distributed, all analyses were performed with logarithmized RTs. For the high conflict condition "unfair opponent", an analysis of variance (ANOVA) for repeated measurements was conducted, with the within-subjects factors "fair vs. unfair money allocation" and "condition" (verum vs. placebo cTBS). All statistical processing was carried out using MATLAB 2015b (The MathWorks, Natick, MA, USA) or SPSS 22 (SPSS Inc., Chicago, USA).

Correlation evaluation

Due to the (for correlational evaluations) relatively small number of participants, no significant correlations were expected as high effect sizes would be necessary (effect sizes between 0.69 and 0.78 (assessed using GPower; Faul, Erdfelder, Buchner, & Lang, 2009)). Therefore, all following calculations were explorative in nature. For all correlation evaluations, the Pearson method was used and the results were Bonferroni corrected for multiple testing (Shaffer, 1995). The scores of the different questionnaires were correlated with both the allocated amount of money towards fair and unfair opponents (for both conditions, verum and placebo) and the ß-values in the right DLPFC. Additionally, the mean amount of allocated money was correlated with cortical activation (ß-values) in channel 25 where the cTBS had been applied.

fNIRS data processing

The data of the fNIRS measurements was exported without pre-processing and analyzed with MATLAB 2015b (The MathWorks, Natick, MA, USA). A bandpass filter excluded all frequencies <0.01Hz and >0.5 Hz. In addition, data were corrected for motion artefacts with the correlation based signal improvement procedure (CBSI; Cui, Bray, & Reiss, 2010); all subsequent analyses were run with the resultant cbsi-hb. For further correction of the data, an Independent Component Analysis (ICA; Delorme & Makeig, 2004) was used to exclude residual artifacts. After the pre-processing of the data, we used a model-based analysis for event-related fNIRS data (M. Plichta, S. Heinzel, A.-C. Ehlis, P. Pauli, & A. Fallgatter, 2007). The statistical tests were performed on the resulting *ß* values (calculated via the following formula: $\beta = (X'X)^{-1}X'Y;\ \varepsilon \sim i.i.d.(O, \delta^2 I)$) using SPSS 22 (SPSS Inc., Chicago, USA). As the fNIRS data was not normally distributed, the non-parametric Wilcoxon test was used to test for activation differences between stimulation conditions in channel 25 in the condition “unfair opponent and fair money allocation” (where the highest cognitive load and therefore the highest difference was expected).

Results

Behavioral data

Acceptance rates (UG) & Monetary Allocation (DG)

The participants accepted 9.74% of the unfair offers and 73.95% of the fair offers. As hypothesized, our results showed that – towards unfair opponents – subjects offered unfair money amounts significantly more often following verum as compared to sham stimulation (p<.05, 60% verum vs. 45% placebo). As expected, this effect was not present in the condition with fair opponents (p>.1, 6% verum vs. 4% placebo). Permutation tests for the double contrast (verum vs. placebo for unfair vs. fair opponents) furthermore indicate a significant interaction between both factors (stimulation × opponent) (p<.05, 53.7% $\text{verum}_{(\text{unfairOpponent-fairOpponent})}$ vs. 40.8% $\text{placebo}_{(\text{unfairOpponent-fairOpponent})}$). These results are depicted in Figure 1[A].

Reaction times towards unfair opponents (DG)

There was a significant main effect of “allocation” (*F*(1,12)=9.373, *p*=.01) with higher RTs for fair amounts (*M*=924.00, *SD*=442.36) and lower RTs for unfair amounts (*M*=718.64, *SD*=334.37), and a significant interaction effect between the two factors “allocation” and “stimulation” (*F*(1,12)=7.765, *p*=.016; see Figure 1[B]). In line with our a priori hypotheses, paired t-tests for post-hoc analyses showed that it took participants significantly longer to make a fair (as compared to unfair) offer towards a previously unfair opponent following inhibitory cTBS ($\text{Difference}_{\text{RT\_fair\_offer-RT\_unfair\_offer}}$=419.07ms; *t*(15)=2.262, *p*=.039), whereas RTs did not differ between fair and unfair offers following placebo stimulation ($\text{Difference}_{\text{RT\_fair\_offer-RT\_unfair\_offer}}$=-8.34ms; *t*(13)=-0.721, *p*=.484).

To sum up the behavioral data, following inhibitory stimulation of the right DLPFC, participants made fair offers to previously unfair opponents significantly less often and – if they chose to do so – it took them significantly longer than to make an unfair offer.

Correlational results

As expected (see above), no correlation remained significant after correcting for multiple testing.

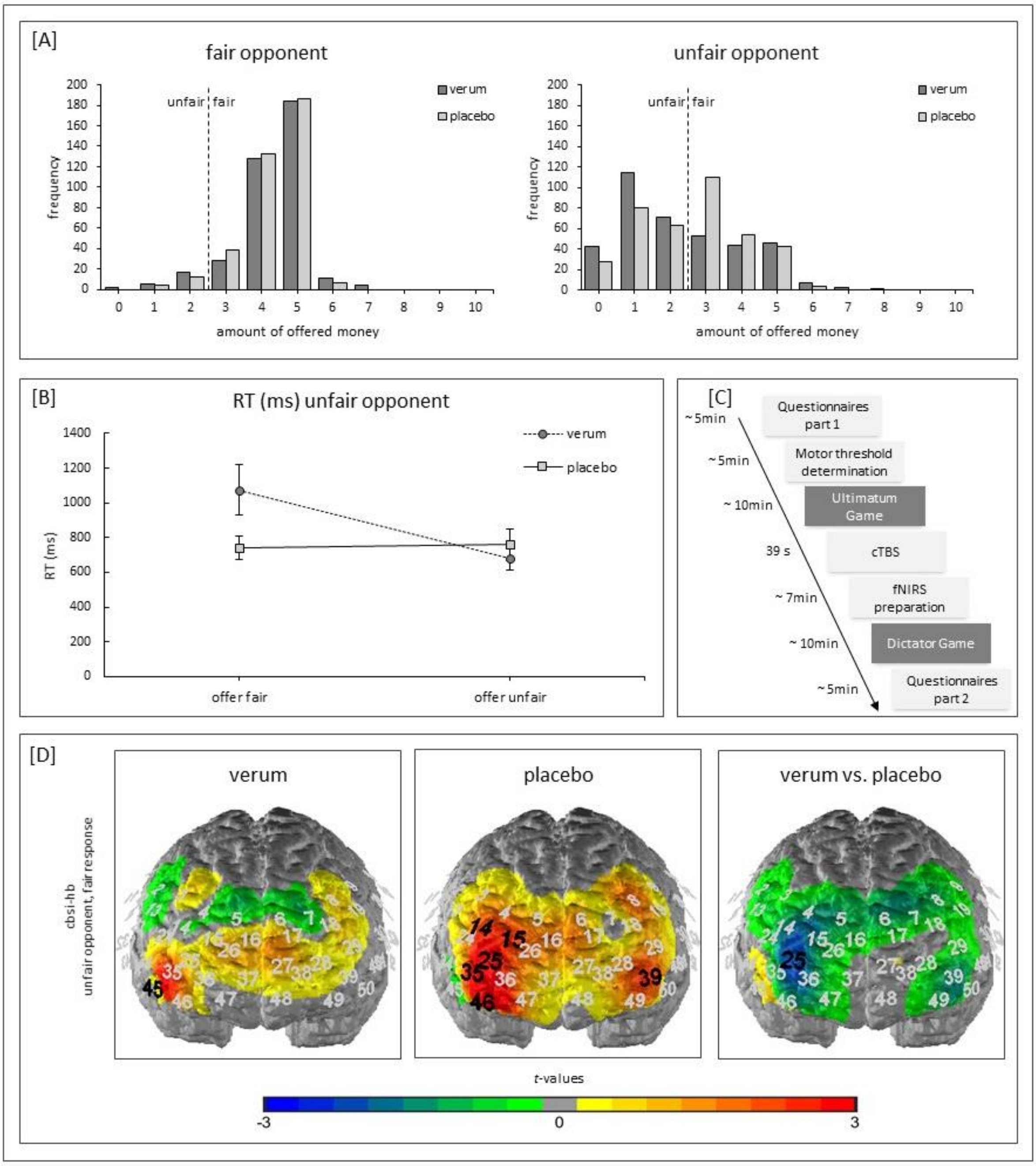

Figure 1: [A] Histogram of the frequencies of the allocated amounts of money (0-10 Euro) over all participants for fair opponents (left; low-conflict condition) and unfair opponents (right; high-conflict condition). The dotted lines indicate the amount of unfair (0-2 Euro) and fair offers (>2 Euro). [B] RT (ms) for fair and unfair offers in the high-conflict condition. Error bars indicate the standard error. [C] Flow chart of the study design [D] t-values in the high-conflict condition for fair responses in the verum and the placebo condition tested against zero and the t-values of the contrast verum vs. placebo. Here, black inked numbers mark significant channels.

fNIRS results

The higher RTs as well as the shift in fair vs. unfair money allocations indicates that the condition “unfair opponent and fair response” is the most critical condition for the subjects in the verum condition. These results confirm our hypothesis that in this condition the requirement for cognitive control is the highest. Therefore, we expect the biggest difference between stimulation protocols (verum vs. placebo) especially in this condition as the DLPFC (as a major cognitive control region) should be specifically involved here. Thus, to further investigate the psychophysiological foundation of this effect, we performed an analysis of activation differences between stimulation protocols (verum vs. sham) specifically for this most critical task condition. In channel 25, which is part of the stimulated right DLPFC, we found a significantly lower activation following verum as compared to sham stimulation (Wilcoxon Test; z=-2.656, p=.008, n=19). The results of this analysis are depicted in Figure 1[D]. Towards fair opponents – in accordance with our expectations (see above) – no significant activation differences between the conditions were observed, neither for unfair responses (Wilcoxon Test; z=-0.966, p=.334, n=19) nor for fair responses (Wilcoxon Test; z=-0.80, p=.936, n=19).

Additional results

For the fairness rating, the desire for revenge as well as for the sympathy rating, no significant differences were observed between the conditions (verum vs. placebo). Between the different opponents (fair vs. unfair), significant differences were found for the fairness rating (M=2.14, SD=0.93; t(18)=9.98, p<.001), the desire for revenge (M=1.59, SD=0.82; t(18)=-8.45, p<.001) and the sympathy rating (M=2.05, SD=0.91, t(18)=9.74, p<.001). The participants were not able to guess which of the two sessions involved verum (as compared to sham) stimulation above chance-level (χ^2(1, N=17)=1.058, p=.303).

Discussion

The results of this study confirm the important role of the cognitive control system (i.e., DLPFC) for forgiveness behavior. Inhibitory TBS of the right DLPFC changed the response tendencies of the participants towards unfair opponents, but not towards fair opponents. An analysis of RTs showed that even if the participants in the stimulated condition assigned a fair amount of money to unfair opponents (which they did significantly less often), they needed significantly more time to do so. Directly confirming inhibitory stimulation effects, we also observed significantly reduced activation within the right DLPFC following verum stimulation during the critical task condition (fair offer towards previously unfair opponent). Importantly, fairness and sympathy ratings (as well as subjective desire for revenge) were not significantly affected by the stimulation protocol, indicating that manipulations of the cognitive control system changed the response outcome, but not underlying affective/motivational response tendencies. While various earlier results (Brüne et al., 2013; Ricciardi et al., 2013b; Will et al., 2014) and also the review of Ochsner and Gross (Ochsner & Gross, 2005) already suggested an important role of the DLPFC for forgiveness and – more generally – the inhibition of unwanted emotional responses, the present study provides initial causal evidence for the crucial involvement of top-down control of unwanted emotional responses (via the right DLPFC) in displaying prosocial behavior towards offenders. The fact that cTBS only impacted behavior towards unfair opponents confirms that the DLPFC interfered only in high-conflict situations where automatic emotional responses needed to be suppressed to act in a forgiving manner. This finding is perfectly in line with the model of cognitive control by Botvinick et al. (M. Botvinick, T. Braver, et al., 2001). According to this model, the ACC acts as a conflict monitor and reports situations involving increased response conflict to the DLPFC which is the actual regulatory device. In the low conflict condition of the present study (fair opponent), a regulatory intervention of the DLPFC was not needed; accordingly, an inhibitory stimulation of the DLPFC had no effect on the allocation of money in this condition. In contrast, for the high conflict condition of this experiment (unfair opponent), a regulatory intervention of the DLPFC was necessary to act in accordance with one’s cognitive/cultural norms (i.e., in a forgiving manner); accordingly, inhibitory stimulation of the DLPFC had a significant effect in this condition.

With a slightly different connotation, it could also be argued that prefrontal inhibitory stimulation allowed participants to act economically by responding with small amounts of money for previously unfair opponents (resulting in more money for themselves), whereby this sort of “retaliating” action may be automatically inhibited due to cultural norms by an intact prefrontal control system following sham stimulation. Yet another alternative interpretation for the results of the present study could be a simple tit-for-tat mechanism which was used by the participants when the cognitive control region was inhibited by cTBS. Giving an opponent the same amount of money they had previously received (from that opponent) requires the lowest amount of cognitive effort for the subjects (cf. Halali, Bereby-Meyer, & Meiran, 2014). For fair opponents, no differences between the conditions are detectable. For unfair opponents, the subjects in the verum condition chose the cognitively least demanding way (i.e., reciprocity) whereas the subjects in the placebo condition still tried to act in accordance with social norms to distribute the money fairly, also towards unfair opponents. According to this explanation, a simple tit-for-tat mechanism – which involves low cognitive load – would be responsible for the difference between stimulation conditions (verum vs. placebo) instead of a lack of inhibiting unwanted, baser emotional responses in the verum condition.

It should be noted that the repeated interactions with the same opponents may have influenced the results. For example, while social/cultural norms generally promote fairness, repeat offenses tend to be punished by society. Previous studies demonstrated that a comparable inhibition of DLPFC activity with cathodal transcranial direct current stimulation (tDCS) can improve goal-directed behavior by counteracting implicit cognitive conflicts (Schroeder, Pfister, Kunde, Nuerk, & Plewnia, 2016). Given these findings and considering the differential effects under fair and unfair offers, our data support the notion of a distinct task-dependency of brain stimulation effects in cognitive trials. Future studies should focus on the specific conditions under which cognitive control functions are recruited to implement forgiveness (vs. revenge) behavior. Concerning this question, very interestingly, van't Wout, Chang, and Sanfey (2010) found that emotional reappraisal can change the behavior in UGs more powerfully than other strategies such as suppression or no regulation of emotions; these different strategies are also known to influence the prefrontal BOLD signal (Goldin, McRae, Ramel, & Gross, 2008). Concerning future research, some limitations of the present study should be considered. Regarding the cognitive control model by Botvinick et al. (M. Botvinick, T. Braver, et al., 2001), it would have been interesting to also measure activation differences in the ACC; unfortunately, with the fNIRS imaging method, measurements are restricted to cortical brain areas. Also, a larger sample of participants with a greater variance of age and educational status would help to put the results of the present study on a broader basis. Considering the great impact of different cultural backgrounds on response behavior in DGs (Engel, 2011), a replication of this study in other cultural surroundings would be interesting. Also, specific gender effects are highly probable to occur (Andreoni & Vesterlund, 2001); therefore, in future studies, a well-balanced male/female ratio would be beneficial to investigate potential effects of sex and gender. In future studies, an excitatory TBS protocol should be additionally employed to test for inverse stimulation effects. In future studies, an excitatory TBS protocol should be additionally employed to test for inverse stimulation effects. Moreover, it would be necessary to use an additional control/placebo stimulation (for example an extra measurement without any stimulation) to clarify the effect of cTBS and the causal relationship between brain and behavior.

Also, financial compensation based on the responses of the subjects could be an interesting addition to the present experiment as it might increase the personal involvement and decrease the probability of prosocial behavior. Based on this study design, clinical implications may be deduced for different situations involving the ability to forgive. This is a very important point of future research given the large influence of forgiveness on wellbeing (Worthington, Witvliet, Pietrini, & Miller, 2007), cardiovascular health (Friedberg, Suchday, & Shelov, 2007) as well as overall mortality (L. L. Toussaint, Owen, & Cheadle, 2012). In conclusion, given the picture-perfect fit of the present results with the model of Botvinick et al. (M. Botvinick, T. Braver, et al., 2001) (confirming previous correlational findings as well as theoretical considerations (e.g.; Pronk et al., 2010; Wilkowski et al., 2010)), it can be assumed that forgiveness is an essential function of cognitive control.

Acknowledgments

We would like to thank Ramona Täglich, Hendrik Laicher and Alexander Krieg for their valuable support with collecting the data and Justin Hudak for the careful language proof reading. The study was supported by the German Research Foundation (Deutsche Forschungsgemeinschaft [DFG] project number EH 388/2-1). Ann-Christine Ehlis was partly supported by IZKF Tübingen (Junior Research Group, grant 2115-0-0).

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7.2. STUDY 2: TO REGULATE OR NOT TO REGULATE: EMOTION REGULATION IN PARTICIPANTS WITH LOW AND HIGH IMPULSIVITY

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Under review

Abstract

Successful emotion regulation plays a key role in psychological health and wellbeing. In this study, we tested emotion regulation abilities and the impact of emotion regulation on a subsequent emotional Stroop task in participants with low vs. high impulsivity. A negative emotion inducing movie scene was presented with either the instruction to suppress or allow all upcoming feelings. This was followed by an emotional Stroop task. To assess the effects of emotion regulation, electromyography (EMG) over the Corrugator Supercilii was applied. Neurophysiological mechanisms were measured with functional near-infrared spectroscopy over frontal brain areas. While for the low impulsive group EMG activation was low independently of the instruction, highly-impulsive participants showed increased EMG activity if they were not explicitly instructed to suppress upcoming feelings. With the same extent of functional connectivity within frontal lobe networks, the low impulsive participants controlled their emotions better (less EMG activation) than the highly impulsive participants. In the Stroop task the low impulsive subjects performed significantly better, the emotion regulation condition had no significant influence on the results. We conclude that the cognitive control network is an essential requirement for emotion regulation. Persons with high cognitive control show implicit capabilities to regulate their emotions, persons with low cognitive control abilities need external instructions (= explicit emotion regulation) to achieve similar low expressions of emotionality.

Keywords: fNIRS, DLPFC, Cognitive Control Network, Cognitive Control, Impulsivity

Introduction

From academic success (Nota, Soresi, & Zimmerman, 2004) to physical health, decreased substance dependence, better personal finances, and less criminal offending outcomes (Moffitt et al., 2011), deliberate cognitive control is often perceived as a key element to a “desirable life” (cf. Inzlicht et al., 2015). Cognitive control is commonly seen as a constitutive resource, which all higher functioning (e.g., mental set shifting, updating and monitoring, and inhibition of prepotent responses; Miyake et al., 2000) is built upon (e.g. E. K. Miller & Cohen, 2001). When it comes to the application of cognitive control in an affective context, the construct of emotion regulation has to be additionally considered. Thereby, the question arises whether there is a connection between cognitive control and the capability to deal with (negative) emotion in a functional (adaptive) way. For the current study, this link is of particular interest: From basal attentional processes to cognitive appraisal and reappraisal, Ochsner and Gross (2005) describe a wide range of possible target points for effects of cognitive control on emotion. Especially mechanics of cognitive change and their neural correlates have been participant to most of the studies examining cognitive control and emotion regulation. Bringing previous findings together, Ochsner and Gross (2005) differentiate between two types of control processes – a direct type and an indirect type. Whereas the direct type relies on a reciprocal connection of the ventral PFC (VPFC) and the orbitofrontal cortex (OFC) with subcortical emotional appraisal systems (e.g., amygdala), the indirect type involves the DLPFC and is assumed to influence appraisal systems only mediately (e.g., via VPFC). With respect to these neurophysiological considerations, Ochsner, Silvers, and Buhle (2012b) outlined a cognitive model describing the multifaceted influence of cognitive control on emotion: From rather proactive influence (situation selection and modification, attentional deployment) to rather reactive influence (cognitive change, response modulation) on emotion, the proposed model includes a wide range of target points for cognitive control. For the paradigm of the current study (emotion induction by means of a short film clip), internal situation modification, attentional processes, appraisal and reappraisal as well as response modulation are of particular interest. The PFC and especially the DLPFC (explicit appraisal processes, Ochsner & Gross, 2005; selective attention and working memory, Ochsner et al., 2012b) are considered to play a crucial role for these processes.

Aiming for an extensive model of cognitive control within the PFC, Ridderinkhof, Van Den Wildenberg, Segalowitz, and Carter (2004) disentangled the role of different PFC substructures for different control processes. At this, their key conclusion is that cognitive control can roughly be divided into two main stages: Detecting errors and conflicting response tendencies, which is associated with the medial frontal cortex (MFC), and implementing appropriate adjustments, which is associated with lateral and orbitofrontal divisions of the PFC. The rostral cingulate zone (RCZ, border zone between BA8, BA6, BA32’ and BA24’) constitutes an important link between these two stages. In particular, interconnectivity between anterior cingulate cortex (ACC; BA 24, BA24’, BA32’) and DLPFC (BA46) areas (Koski & Paus, 2000) via the RCZ seems to play a crucial role for a cognitive control network (CCN) within the PFC. The idea of a superordinate CCN is also seized by Niendam et al. (2012): In their meta-analysis, they gather evidence for connectivity patterns involving dorsolateral prefrontal, anterior cingulate, and parietal cortices. Taking into account that regulation processes can only be understood as a complex interplay of multiple neural structures, past studies have often drawn on functional connectivity analyses to examine the CCN. Further, functional connectivity analyses of Raz et al. (2016) support a domain-general network model about how emotions are represented on a neural level – their results strengthen the assumption that there might be something like a common neural network for different emotions (e.g. Barrett, 2006). Besides structures of the ventral stream, Raz et al. (2016) additionally highlight the fundamental role of increased functional connectivity between dorsal and ventral structures during emotion induction. Referring to the neural model by Ochsner and Gross (2005), it might be concluded – with some limitations – that also the direct (ventral) and the indirect (dorsal) type of control processes interact considerably. A differentiated view on the interplay of distinct aspects of regulation processes might therefore help to identify factors determining success or failure of cognitive control (of emotion).

While CCN studies and meta-analyses have mainly been conducted from a rather micro-analytic view on the PFC, connectivity studies examining emotion regulation processes have been conducted from a rather macro-analytic view on the interplay between cortical and subcortical structures. In this study, we aim to combine connectivity analysis with a differentiated look on *within-PFC-connectivity* during emotion regulation processes. At this, the role of the DLPFC and its substructure BA46 as an important link between CNN components DLPFC and MFC (Ridderinkhof et al., 2004) is of particular interest. Furthermore, while most research so far has focused either upon the influence of emotion on cognitive control (e.g. Gray & Braver, 2002) or upon the influence of cognitive control on emotion (e.g. Ochsner & Gross, 2005), we consider both directions here. Considering that – at least partially – the same brain structures were found to play a role for both directions of influence (e.g., the DLPFC), a reciprocal interference seems very likely.

To further address this question, we combined negative emotion induction, an emotional Stroop task and a high- vs. low-impulsive sample with optical imaging of relevant PFC substructures (fNIRS = functional near-infrared spectroscopy) and electromyography (EMG) over the corrugator supercilii as an indicator of negative emotion (cf., Cacioppo et al., 1986; Lang et al., 1993). In detail, two subsamples (high- vs. low-impulsive participant groups) were compared regarding the interplay of cognitive control and emotion. A classification according to impulsivity is based upon the stable connection between impulsivity and aspects of cognitive control (e.g. Herrmann et al., 2010; Logan, Schachar, & Tannock, 1997), with high impulsivity being associated with reduced cognitive control capacity. During the experiment, each person passes through negative emotion induction after having been instructed to suppress or allow upcoming feelings. At this point, the influence of cognitive control (high vs. low) on the down-regulation of negative emotions can be observed in EMG data. With the implementation of the instructions as a between-participants factor two things can be assessed; first the ability of high vs. low impulsive participants to regulate their emotions, and secondly the influence of this emotion regulation on subsequent task performance. In a second step, each participant then completes a modified emotional Stroop task, which requires cognitive control to overcome an emotion-based cognitive conflict. At that point, the influence of emotion on cognitive control performance becomes apparent. Regarding underlying neurophysiological correlates, a closer look at the interplay of PFC substructures within the CCN with the help of functional connectivity analyses is particularly interesting. Considering previous research and established assumptions as presented above, we suggest the following hypotheses:

Highly-impulsive participants show more muscle contraction of the Corrugator Supercilii, decreased connectivity within the cognitive control region DLPFC and poorer performance on the emotional Stroop task in comparison with persons of the low-impulsive group. Since negative emotions were found to aggravate cognitive control performance with verbal stimuli (Gray & Braver, 2002), we expect participants to show increased DLPFC activation and better performance in the subsequent emotional Stroop task when emotion induction has taken place with proactive suppression in comparison to the “allow all upcoming feelings” condition. With respect to findings that cognitive control is involved in emotion processing in general (Ochsner & Gross, 2005) and in down-regulating negative emotions specifically (Ochsner et al., 2012b), we also expect that proactive suppression of feelings during emotion induction is less effectual for the low- than for the highly-impulsive group (= interaction effect of group and instruction on EMG activation, connectivity patterns and emotional Stroop task performance). Regarding connectivity data and the CCN, we assume that the interplay between PFC structures is significantly increased for low-impulsive vs. high-impulsive participants and for the suppress vs. allow instruction.

Methods

Participants

57 participants participated in this study; 48 of them were female. The mean age was 22.8 years (*SD*=2.8) and all of them were students at the University of Tuebingen. Levels of impulsivity were measured using the Adult ADHD Self-Report Scale (ASRS), with participants with scores < 10 categorized as having "low impulsivity" and participants with scores between 15 and 23 categorized as having "high impulsivity". 27 of the participants were assigned to the low-impulsive group, 34 of the participants were assigned to the highly-impulsive group. To avoid comorbidities commonly associated with ADHD, participants with high impulsivity – but without an ADHD diagnosis and with ASRS scores of no more than 23 – were selected for the highly-impulsive group. Regarding sex and age, the groups did not differ significantly. All participants were given either money (10 € per hour) or course credit for compensation.

Questionnaires

Additionally to the ASRS, the experienced anger, fear and sadness were measured with a Likert scale from 0 to 5, for investigating potential differences in the experienced emotions between the groups and the instructions.

Justification of Sample Size

For the determination of the sample size, the effect sizes of the study of Marsh, Dougherty, Mathias, Moeller, and Hicks (2002) were used. In this study the scores in different cognitive control tasks of highly and low impulsive woman were compared. The effect size was between 0.19 and 0.27 Cohens *f* (Cohen, 1988). Using G*Power (Faul et al., 2009) an estimated sample size between 32 and 62 for significant interaction effects was assessed.

Design

This study was a 2 (low vs. high impulsive) × 2 (instruction allow vs. suppress upcoming feelings) between-participants design with one measurement per participant. This design was chosen to avoid carry-over effects.

Emotion induction paradigm

In all participants, negative emotions were induced with a 4-minute film clip. Stereo sound was implemented with two standard PC speakers positioned on both sides of the monitor (standardized volume across all participants, peaks approximately 80 dB). The shown material was taken from the movie Sophie's Choice (Pakula, 2007) and has already been used successfully for emotion induction in previous studies (e.g., Möbius et al., 2017; Fitzgerald et al., 2011). The presented scene features a sadistic concentration camp supervisor forcing a polish woman to decide upon one of her two kids to be killed. The wording of the preceding instruction (allow vs. suppress upcoming feelings) was adapted from Gross (1998) and Hayes et al. (2010).

Emotional Stroop task

Directly after the emotion induction, with a short break of approximately 3 minutes, the emotional Stroop task started (Watts, McKenna, Sharrock, & Trezise, 1986). The task consisted of negative, positive and neutral word lists à 10 stimuli (based on stimuli of Smith and Waterman (2003)). All of these 30 words were presented in 4 different colors (red, green, blue, and yellow), resulting in 120 different stimuli, which were displayed centrally against a black background. Responses were given by means of a high frequency button box with four buttons (one for each color), allowing precise recording of reaction times. A button-color-assignment was displayed during the whole experiment. After 20 training trials and a fNIRS baseline scan (20 seconds), the experiment started with a white fixation cross (200 ms) followed by a target stimulus remaining on screen until a response was given (timeout after 1000 ms). In case of a wrong button press, no error message appeared. Between the trials a black screen for a jittered (M. Plichta et al., 2007) period of 4000-7000 ms appeared.

EMG

To record the EMG, a BrainAmpExG MR 16 channel system amplifier was used. Two EMG electrodes were applied over the left Corrugator Supercilii. For correcting the EMG data, vertical (VEOG) and orthogonal electrooculography (OEOG) was additionally applied; as ground, Fz according to the international 10-20 system (Jasper, 1958b) was used. The sampling rate was 1000 Hz; an online cutoff filter for data <0.1 Hz and >70 Hz and a Notch filter of 50 Hz was applied.

EMG analyses

In total, 13 participants had to be excluded from the EMG analysis (4 because of hardware malfunction, 3 because of software malfunction, 6 because they were outliers [defined as two standard deviations over/under the overall mean standard deviation]; the exclusions were evenly distributed over all groups). All analyses were run using Brain Vision Analyzer (Brain Products GmbH, Gilching). Preprocessing of the EMG data was adapted from Elkins-Brown, Saunders, and Inzlicht (2016). Blink artifacts were corrected via automatic ocular correction; an IIR bandpass filter (28–499 Hz) and a 50 Hz notch filter were applied with an additional moving average correction (20 ms). Afterwards, the data was split into 12 segments of 20 seconds, a Fast-Fourier-Transformation was applied, and a mean for each segment was calculated. In accordance with related works (e.g. Van Boxtel, 2001; Van Boxtel, 2010), the mean of the spectrum between 60 Hz and 85 Hz was exported separately for each participant and time point. With SPSS 22 (SPSS Inc., Chicago, USA), a 2×2×12 ANOVA for repeated measurements was run with the between-participants factors instruction and group and the within-participants factor time. For post-hoc analysis, we merged the data over all time points and ran paired t-tests for both instruction conditions.

fNIRS

With fNIRS, which is a non-invasive optical imaging technique, an in-vivo measurement of changes in the concentration of oxygenated (O_2Hb) and deoxygenated (HHb) hemoglobin in cortical brain tissue is possible. The ETG-4000 Optical Topography System (Hitachi Medical Co., Japan) was used to conduct the fNIRS measurements. This is a continuous wave system with two different wavelengths (695±20 and 830±20 nm) and a temporal resolution of up to 10 Hz. A 3 × 11 probeset with 52 channels, 16 detectors and 17 emitters, and an inter-optode distance of 3 cm placed over left and right frontopolar areas was used. In accordance with the international 10-20 system (Jasper, 1958b), the medial optode in the bottom row was located on Fpz and symmetrically oriented towards T3/T4.

fNIRS data pre-processing

The raw data of the fNIRS measurements was exported, and analyses were run with MATLAB 2015b (The MathWorks, Natick, MA, USA). All frequencies <0.01 Hz and >0.5 Hz were excluded via a bandpass filter. Additionally, a correlation based signal improvement (CBSI; Cui et al., 2010) procedure was applied for the correction of motion artefacts. All further analyses were run with the calculated cbsi-hb. For the exclusion of high amplitude artefacts, an Independent Component Analysis (ICA; Delorme & Makeig, 2004) was used. Thereafter, all signals were visually inspected for remaining artefacts after the described pre-processing. In case of visible artefacts, the channels were interpolated from surrounding channels. Subsequently, the mean activation in the different regions of interest (ROI) was exported for all further analyses. As they are part of the CCN, the following ROIs were exported: Left- and right hemispheric Brodmann areas 9, 10 and 46 and the gyrus frontalis inferior (IFG). The channel allocation to the different ROIs was determined based on Tsuzuki et al. (2007), Singh, Okamoto, Dan, Jurcak, and Dan (2005) and Rorden and Brett (2000).

fNIRS connectivity analyses

Further, functional connectivity (FC) was computed by Pearson correlations after correcting for outliers for data of each channel pair. Correlation coefficients were normalized by Fishers r-to-z transformation. In the following, we used the analysis strategy proposed by Zhu et al. (2017). FC was compared within the predefined ROIs (average correlation of all channels within the ROI) and between the ROIs and the other brain areas that were covered by the probeset (average correlation between the channels of the ROI and the channels of a given brain area) (Zhu et al., 2017).

Statistical processing: Stroop data

All analyses of the Stroop data were run with SPSS 22 (SPSS Inc., Chicago, USA). For all analyses the inversed efficiency score ($IES = \frac{RT}{1-Proportion\ of\ errors}$; Townsend and Ashby (1983)) was used. Outlier trials (more than 2 standard deviations difference from the mean per person, in total 3.72% of the data) and incorrect trials were excluded from the analyses. To test the presence of an emotional Stroop effect (and corresponding influences of the independent variables), a 2 x 2 x 3 repeated-measures ANOVA was conducted: between-participants factors were cognitive control (high- vs. low-impulsive group) and instruction preceding the emotion induction (suppress vs. allow upcoming feelings); within-participants factor was stimulus valence (neutral vs. negative vs.

positive). As post-hoc analysis, further one-way ANOVAs with IES as dependent variable and instruction as single factor were conducted for each group separately.

Statistical processing: Correlations

Correlations were calculated with the global connectivity, the EMG values for time segment 11 (most arousing sequence of the film clip and highest activation over all participants) and the overall IES score in the Stroop task. The Pearson method was used for each group and condition separately (low vs. highly impulsive, suppress vs. allow) and a Bonferroni correction for multiple testing was applied (resulting α-value: 0.016).

Results

Emotion induction – EMG results

The 2×2×12 ANOVA (group × instruction × time) revealed a significant main effect of time ($F(11, 43)=16.864$, $p<.001$, $\eta^2=.282$), a main effect of group ($F(11, 43)=7.266$, $p=.010$, $\eta^2=.145$; $M_{\mathrm{LowImpulsive}}=0.40\ \mu V^2/Hz$, $M_{\mathrm{HighlyImpulsive}}=1.03\ \mu V^2/Hz$), a main effect of instruction ($F(11, 43)=6.863$, $p=.012$, $\eta^2=.138$; $M_{\mathrm{Suppress}}=0.40\ \mu V^2/Hz$, $M_{\mathrm{Allow}}=1.02\ \mu V^2/Hz$), an interaction effect of time and group ($F(11, 43)=4.358$, $p<.001$, $\eta^2=.092$), an interaction effect of instruction and time ($F(11, 43)=2.87$, $p=.001$, $\eta^2=.062$) and an interaction effect of group and instruction ($F(11, 43)=4.008$, $p=.049$, $\eta^2=.087$). As the interaction of group and instruction is directly related to our hypotheses, we performed a post-hoc testing, merged the data for time and ran (separately for each group) a t-test for independent measurements. In accordance with our hypotheses, no significant difference between the conditions (instruction allow vs. suppress) was found in the low impulsive group ($t(20)=0.872$, $p=.393$), whereas in highly impulsive participants ($t(23)=2.623$, $p=.015$) the muscle activity differed significantly between the instructions with higher values in the instruction condition allow ($1.57\ \mu V^2/Hz$ vs. $0.48\ \mu V^2/Hz$; see Fig. 1).

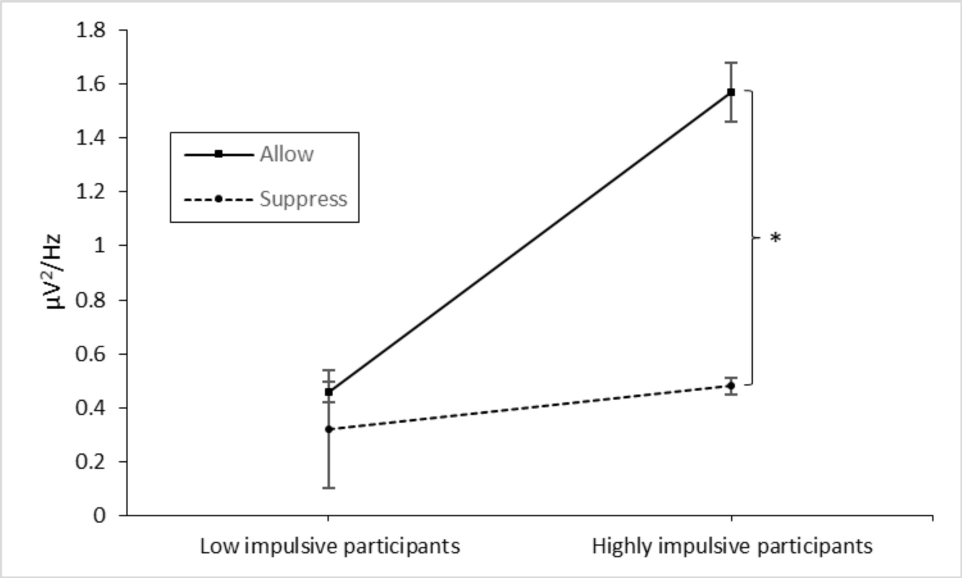

Figure 1: Muscle activity over the corrugator supercilii in the *allow* and *suppress* condition, separated for the low- and highly impulsive group. Error bars indicate the standard error; the star indicates the significant difference between the conditions in the high impulsive group.

Emotion induction – Connectivity results

In the connectivity analyses, no interaction effects and no group effects were found. After Armitage-Parmar correction for multiple testing, the correlation between the right DLPFC (BA46) and the left DLPFC (BA46; *p*=.0226) as well as the correlations between the left DLPFC (BA46) and the right and left frontopolar area (BA10; *p*=.0352; *p*=.0135) remained significant. Briefly, significantly stronger connectivity was observed between these different response regions for *suppressing all upcoming feelings* compared to the *allow all upcoming feelings* condition. In figure 2, the contrast of the correlation for instruction suppress minus instruction allow is depicted.

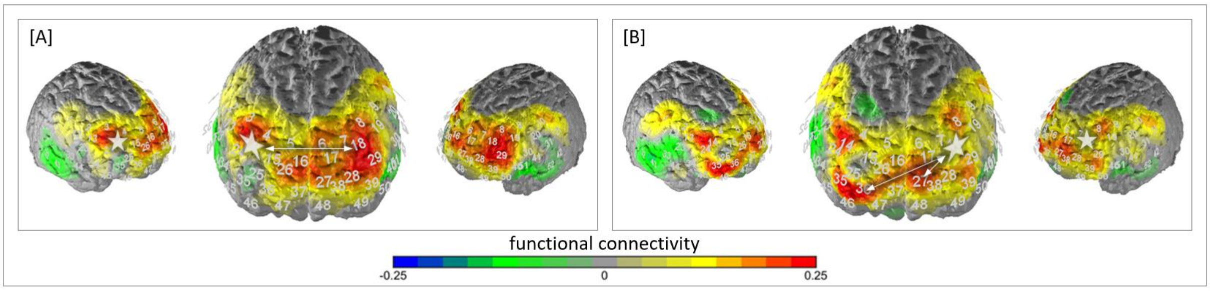

Figure 2: Contrasted connectivity (instruction *suppress* – instruction *allow*) for the seed regions (marked with a white star) right DLPFC [A] and left frontopolar area [B]. Functional connectivity is indicated by the different colours; the white arrows indicate significant correlations.

Stroop task – Behavioral results

Statistical analysis (2×2×3 repeated-measures ANOVA with mixed factors group, instruction and stimulus valence) showed no significant influence of stimulus valence on behavioral data: Neither the main effect ($F(2,114)=0.36$, $p=.701$) nor any interactions with other factors (with group: $F(2,114)=1.88$, $p=.157$; with instruction: $F(2,114)=1.51$, $p=.226$; with group and instruction: $F(2,114)=1.64$, $p=.198$) were significant. Stimulus valence did not influence response speed or correctness in any case. Therefore, the stimulus valence was merged, and the results of the Stroop task used as a general measurement of cognitive control abilities; RTs, proportion of errors and the IES are listed in table 1.

Table 1: *Mean RTs (in ms), mean error rates (in percent) and mean IES (in ms) for all trials of all factor level combinations (SD in brackets).*

	Low-impulsive group (*N* = 27)		High-impulsive group (*N* = 34)	
	Instr. Suppress	Instr. Allow	Instr. Suppress	Instr. Allow
Mean RT	568 (150)	572 (135)	600 (139)	619 (153)
Mean error rates	11.7 (5.8)	11.5 (7.2)	13.3 (6.6)	17.0 (8.8)
Mean IES	647 (180)	651 (166)	700 (186)	758 (218)

The analysis showed a significant main effect of group on IES ($F(1,57)=8.92$, $p=.004$, $\eta^2=.013$). Participants of the low-impulsive group ($M=649$ ms) reached a significantly smaller (better) mean IES ($t(57)=-2.99$, $p=.004$) than participants of the high-impulsive group ($M=737$ ms). However, neither a significant main effect of instruction on IES ($F(1,57)=1.62$, $p=.209$, $\eta^2=.02$) nor a significant interaction between group and instruction ($F(1,57)=1.14$, $p=.289$, , $\eta^2=.02$) could be found.

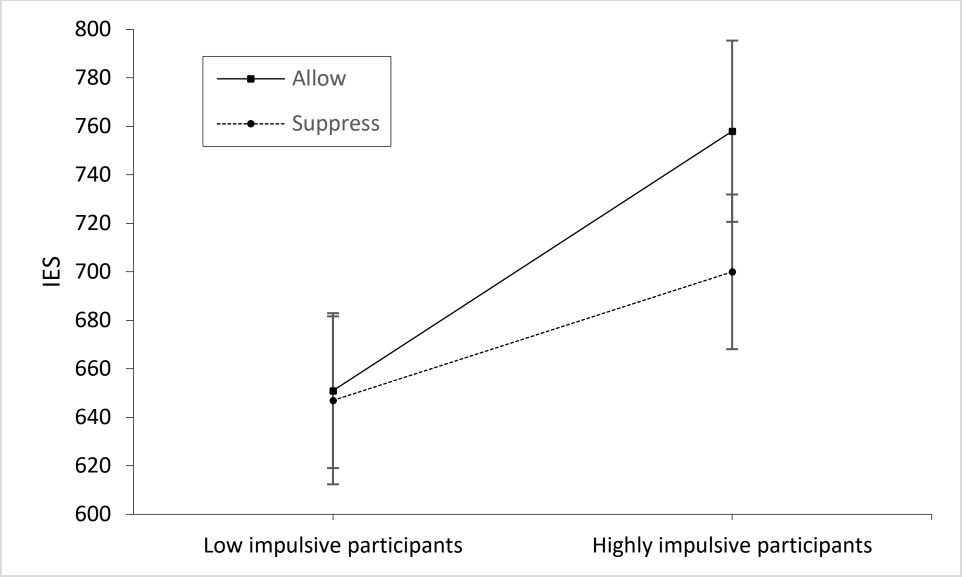

Figure 3: IES scores of the low- and highly impulsive group separated for the allow- and suppress instruction. Error bars indicate the standard error.

Correlational results

In the low impulsive group with the instruction to allow all upcoming feelings, we found a significant correlation between the global connectivity and the IES (*r*(9)=.712, *p*=.014) as well as the EMG activation and the IES (*r*(9)=.721, *p*=.012). In both cases, higher connectivity and EMG activation were associated with higher (worse) IES. In the other group and conditions, no correlation was significant (see all correlations in table 2).

Table 2: *Correlations between EMG, connectivity and IES for the different groups and conditions.*

Group	Instruction	EMG – Connectivity	Connectivity – IES	EMG – IES
Low impulsive	Allow	r(9)=.405, p=.217	r(9)=.712, p=.014*	r(9)=.721, p=.012*
	Suppress	r(8)=-.473, p=.168	r(8)=-.464, p=.151	r(8)=-.030, p=.935
Highly impulsive	Allow	r(11)=-.313, p=.298	r(11)=-.277, p=.360	r(11)=.254, p=.402
	Suppress	r(10)=-.086, p=.789	r(10)=.134, p=.678	r(10)=.356, p=.256

**significant for Bonferroni corrected α=.0167*

Questionnaires

The experienced emotions (fear, anger, sadness) did not differ, neither for group nor for instruction.

Discussion

The study at hand aimed to investigate the effects of emotion regulation (vs. no emotion regulation) on highly vs. low impulsive participants and the underlying functional connectivity within the CCN. In line with our hypotheses, we found a significant effect of impulsivity (group) on both EMG activation during the emotion induction and subsequent Stroop performance. Highly impulsive participants showed, independent of the instruction, higher EMG activation and worse performance in the emotional Stroop task. No group effect was found for connectivity of the DLPFC during the emotion induction. Main effects of the instruction were found on EMG activation – with significantly higher values for the instruction allow – and in the connectivity analyses – with significantly higher correlations between the right and left DLPFC (BA46) as well as the left DLPFC and the right and left frontopolar area (BA10) in the suppress condition compared to the allow condition. For the emotional Stroop task performance, no significant difference between the instruction conditions was found. As hypothesized, an interaction effect of group and instruction was found for the EMG activation, with a significant difference between the instruction conditions for highly impulsive participants only. For the connectivity analysis and the emotional Stroop task, such an interaction effect was not found. Significant correlations between IES and global connectivity as well as EMG activity were found for low impulsive participants in the allow condition.

The significant main effect of the instruction in the EMG data shows the proper effect of our manipulation and confirms the connection between negative emotions and the activation of the Corrugator Supercilii, which is well described in the literature (e.g., Cacioppo et al., 1986; Lang et al., 1993). The overall higher EMG activation during the emotion induction in highly impulsive participants confirms the assumption that emotion regulation in general requires cognitive control. The significant interaction effect, which was found for group and instruction for the EMG activation during the emotion induction, illustrates the expected ceiling effect in low impulsive participants: While persons with high cognitive control seem to implicitly regulate their emotions independent of external stimuli (like the instruction to suppress vs. allow), persons with low cognitive control might need external cues (in this study the instruction to suppress upcoming feelings) to regulate their emotions to the same extent as low impulsive participants. This result indicates the efficiency and usefulness of instructions (like they are used in cognitive behavioral therapy) to regulate negative emotions. While in the low impulsive group (= high cognitive control) a ceiling effect seemed to limit the impact of emotion regulation instructions, this external stimulus had an effect in the highly-impulsive (i.e., low cognitive control) group. The connection of both explicit and implicit emotion regulation with cognitive control mechanisms is well described (cf. Egner, Etkin, Gale, & Hirsch, 2007; Gyurak, Gross, & Etkin, 2011). Strengthening of cognitive control can potentially be considered a general therapeutic approach: In this context, Wolkenstein and Plewnia (2013) successfully examined neuromodulation (transcranial direct current stimulation of the DLPFC) as a method to enhance cognitive control in a depressive sample. Considering that Vanderhasselt and De Raedt (2009) found a relation between improved cognitive control and fewer depressive episodes, approaches like this seem promising for clinical application (Siegle, Ghinassi, & Thase, 2007). Surprisingly, we found no group effect in functional connectivity between the investigated brain areas. While there are several possible explanations (one of which could be an insufficient sample size), this finding might suggest that low impulsive participants achieved a better control of their emotions than highly impulsive participants with the same extent of connectivity, which would then indicate a more efficient use of frontal brain networks in the low impulsive group. Alternatively, group differences in EMG activation (and the following Stroop performance) may have been related to differences in brain areas which were not measured by our fNIRS probe set (e.g. the ACC; Koski & Paus, 2000). The increased connectivity during active emotion regulation, especially between BA46/DLPFC and other frontal lobe areas, could be interpreted as confirmation of the CCN model (Koski & Paus, 2000; Ridderinkhof et al., 2004) and the probable need of cognitive control to effectively regulate emotions. It is also in accordance with the model of Ochsner and Gross (2005) which allocates reappraisal processes (cf. instruction conditions) especially to the DLPFC. The fact that these instructional effects (of suppress vs. allow upcoming emotions) did not impact behavioral data in the emotional Stroop task could be due to the delay between the emotion induction and subsequent task performance. This delay of approximately 5 minutes – together with a limited number of participants in the different groups – could have decreased potential effects to non-significance as a numerical difference is notable (at least in the highly impulsive group; see Figure 3).

Keeping in mind that especially BA46 was involved in the regulation of negative emotions, a specialized therapeutic approach comparable to the one used by Wolkenstein and Plewnia (2013) could be developed using neuromodulation to treat patients with clinically relevant emotion regulation problems. Therefore, in future studies, the effect of transcranial direct current or transcranial magnetic stimulation of the DLPFC – or more specifically BA46 – on emotion regulation in participants with reduced cognitive control should be investigated. Also, causal conclusions considering the involvement of the DLPFC on emotion regulation would be possible with a combination of the current study design with neuromodulation. With a bigger sample (taking the four experimental groups of the study design into account), potential effects of sex and handedness could be investigated as well in future studies.

The interpretation of the correlations should be treated with caution due to the limited number of participants in the single groups, which also made it hard to detect significant correlations after correcting for multiple testing. Nevertheless, significant correlations between global connectivity and EMG activation with higher (=worse) IES in the low impulsive group (allow condition only) suggests a connection between participants who need more frontal connectivity to (implicitly) control themselves during negative emotion induction and a reduced performance in the emotional Stroop task. Significant correlations only in this subgroup could be explained with the high variability in this group (high cognitive resources and no forced emotion regulation).

Partly contrary results were found by Niven, Totterdell, Miles, Webb, and Sheeran (2013). In this study in participants with (perceived) low self-control the blood glucose level (which is an indicator for self-control abilities) decreased after emotion regulation. In this study we found in the Stroop task after the emotion induction especially in the low impulsive group a (only numerical) effect in the opposite direction. Without any emotion regulation the participants were worse in the Stroop task. This could be, with some limitations due to the missing significance, interpreted that the experience of negative emotions is influencing the cognitive control stronger than potential depletion effects. This seems to be especially the case in participants with a-priori low cognitive control resources.

Based on this study, we conclude that the CCN is an essential requirement for emotion regulation; especially BA46 seems to play a crucial role. While persons with high cognitive control show implicit capabilities to regulate their emotions during a negative emotion induction independent of external instructions, persons with low cognitive control abilities need external instructions (= explicit emotion regulation) to achieve similar low expressions of emotionality.

Acknowledgements

We would like to thank Ramona Täglich, Alexander Krieg and Hendrik Laicher for their exceptional support with collecting the data. This study was supported by the German Research Foundation (Deutsche Forschungsgemeinschaft [DFG] project number EH 388/2-1). Ann-Christine Ehlis was partly supported by IZKF Tübingen (Junior Research Group, grant 2115-0-0).

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7.3. STUDY 3: DISINHIBITED REVENGE – AN FNIRS STUDY ON FORGIVENESS AND COGNITIVE CONTROL

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Under review

Abstract

The ability to reconcile is a key factor for a cooperative and successful life. Among the manifold factors that impact on how people negotiate social contracts, poor cognitive control (which is inversely linked to impulsivity) may exert negative effects on forgiveness. To investigate the neurobiological basis of this proposition, subjects with high vs. low impulsivity scores completed an ultimatum game (UG) and a dictator game (DG). First the participants played an UG where they had to accept or reject offers from fair or unfair opponents. Afterwards, the roles changed, and a DG was played. Here, subjects had the opportunity to forgive or take revenge towards the unfair opponents by the allocation of a fair/unfair amount of money. During this task, activity of the dorsolateral prefrontal cortex (DLPFC) was assessed via functional near-infrared spectroscopy (fNIRS). Highly impulsive subjects were significantly more revenge-seeking than low impulsive individuals. This behavioral difference was reflected in the activation pattern of the left DLPFC, where higher activation in trials with unfair opponents was found, but only in the highly impulsive group. This result is discussed as an indicator for a more revenge-driven behavior in highly impulsive individuals, as activity in the left DLPFC is associated with retaliation.

Introduction

''*The weak can never forgive. Forgiveness is an attribute of the strong.*'' (Gandhi)

Stability of social relations, academic success, potential conflicts with the law – all these highly relevant factors for a desirable life are strongly correlated with the concept of cognitive control (e.g. Inzlicht et al., 2015; Moffitt et al., 2011; Nota et al., 2004). While persons with high cognitive control are successful in various areas of life, a lack of cognitive control is often associated with poor psychosocial functioning. Several neuropsychiatric disorders such as ADHD (e.g. Barth et al., 2015), drug dependence (e.g. Barth et al., 2015; Verdejo-Garcıa, López-Torrecillas, de Arcos, & Pérez-Garcıa, 2005) or Borderline Personality Disorder (Brüne, 2016) frequently display low states of cognitive control. Moreover, rumination – which is strongly connected with depression – is associated with a lack of cognitive control (Rosenbaum et al., 2017; Rosenbaum, Thomas, et al., 2018), while conversely, therapeutic approaches to reduce rumination aim at improving cognitive control (Rosenbaum, Maier, et al., 2018). Cognitive control mainly consists of the three neuropsychological subfunctions; updating, shifting, and inhibition (Miyake et al., 2000). Accordingly, updating can be seen as the persistent monitoring and task-based removal/adding of relevant content, while shifting describes a flexible moving between different tasks or mental sets and inhibition is defined as the suppression of prepotent (but not goal-oriented) response tendencies (Miyake & Friedman, 2012). Generally, cognitive control is negatively correlated with impulsivity (e.g. Bari & Robbins, 2013).

Cognitive control plays a central role in the negotiation of social contracts of all kinds, including deception and reconciliation (Karremans and van der Wal, 2013: commentary on Kurzban et al, BBS article). The importance of successful forgiveness, for example, is underlined by associations with general health outcomes (and especially cardiovascular health (Friedberg et al., 2007)), stress perception (Worthington et al., 2007) and overall mortality (L. L. Toussaint et al., 2012). Forgiveness can be described as a fluent process which consists of two steps; first, the decision to forgive the provocateur, and second, the inhibition of revenge-seeking feelings (Fincham, Hall, & Beach, 2006; Wilkowski et al., 2010). These feelings, like anger and hate, are according to Pingleton (1989) the natural reflexive response to transgressions. Therefore, especially inhibition (as a subfunction of cognitive control) is discussed as a key factor for successful reconciliation. Neurobiologically, the conflict monitoring theory (M. M. Botvinick, T. S. Braver, D. M. Barch, C. S. Carter, and J. D. Cohen (2001), posits that potential response conflicts (e.g., the decision to forgive vs. the impulsive desire for revenge) are associated with activation of the anterior cingulate cortex (ACC), which signals an increased need for the implementation of cognitive control to the dorsolateral prefrontal cortex (DLPFC; e.g. Egner & Hirsch, 2005b; Kerns et al., 2004). According to this conceptual embedding, differences between high- and low forgiving individuals should be visible especially in the DLPFC.

However, it should be noted that beside the DLPFC other brain areas are involved in forgiveness. For example, Ricciardi et al. (2013a) found significant covariations between the anterior cingulate cortex (ACC), the DLPFC and the inferior frontal gyrus (IFG) during forgiveness processes. According to the authors, the ACC is associated with affective and emotional processing in forgiveness (Bush et al., 2000), while the IFG is associated with cognitive and emotional empathy (Shamay-Tsoory et al., 2009). Although, other brain regions are important for a complex cognitive process as forgiveness, the DLPFC has been selected as the area of interest in this study as this brain region is thought to control areas such as the IFG and ACC during forgiveness processes (Clark 2005).

To study the neurobiological basis of revenge and forgiveness, Brüne et al. (2013) developed a study design, which enabled the participants to forgive unfair opponents or to take revenge in a controllable experimental setting. To this end, the participants first played an ultimatum game (UG) where a virtual opponent split up 10 Euro on each trial and the participants had to accept or reject the offer. During the game, the participants learned implicitly that half of the opponents were fair (offers between 3 and 5 Euro) and the other half were unfair (offers between 0 and 2 Euro). Subsequently, the roles changed and the subjects had to split up 10 Euro between themselves and the previous opponents in a dictator game (DG). Here, subjects had the possibility to forgive their previously unfair opponents or to take revenge. The slight difference between the UG and the DG considering rejection possibilities is important to note: Since the opponents had no possibility to reject an offer made by the participants in the DG, the subjects were able to allocate the money without any fear of rejection. In their study, Brüne et al. (2013) found a significantly higher activation of the right DLPFC when the subjects “forgave” their previously unfair opponents (by allocating a fair amount of money themselves) in comparison to allocating a fair amount of money to a previously fair opponent. This result can be interpreted as an indicator that forgiveness processes are (partly) controlled by the DLPFC and thus by a classical cognitive control region. To further assess the causality of this finding, Maier et al. (2018) combined the paradigm of Brüne et al. (2013) with an inhibitory continuous theta-burst stimulation (cTBS, Huang et al., 2005) in order to test the effects of a reduced activity in the right DLPFC on forgiveness behavior. In this study, reduced forgiveness (i.e., more revenge seeking) behavior towards previously unfair opponents was found after inhibition of the right DLPFC via cTBS. The experienced emotions towards the opponents were in both conditions the same, strong negative emotions towards the unfair opponents and positive emotions towards the fair opponents. Along similar lines, Müller-Leinß, Enzi, Flasbeck and Brüne (2017) found in a study using repetitive transcranial magnetic stimulation (rTMS) that inhibition of the right DLPFC not only led to an increased punishment of previously unfair opponents, but also less fair behavior toward previously fair players, suggesting maximization of one's own monetary benefit in a "homo economicus"-like fashion.

To further investigate the connection between cognitive control and forgiveness behavior, the question arises how forgiveness behavior differs between subjects with high- vs. low cognitive control. If subjects with low cognitive control would act in a less forgiving manner, it would indicate that this subgroup fails in inhibiting revenge seeking feelings. To clarify this potential correlation, we compared subjects with high vs. low cognitive control (as defined by low vs. high impulsivity scores) with the combination of an UG and a DG. For controlling the cognitive control abilities of the subjects in an objective and reliable way an Emotional Stroop-task was used to assess both, cognitive control and implicit emotions. In the Emotional-Stroop task, the color words of the classical Stroop-task are replaced with emotional vs. non-emotional words. With this task, which was run after the UG and DG it was possible to measure both, the cognitive control and the implicit emotionality of the participants. Based on previous work using this paradigm (Brüne et al., 2013; Müller-Leinß et al., 2017; Maier et al., 2018) and the outlined theoretical considerations, we propose the following hypotheses: Subjects with low cognitive control will allocate unfair amounts of money to unfair opponents more often than subjects with high cognitive control (i.e. more impulsive retaliation). Towards the fair opponents, we expect no differences between groups, because the interaction lacks the provocation of revenge. These specific effects should be accompanied by activation differences in the right DLPFC: We expect significantly less activation in the right DLPFC in subjects with low cognitive control compared to subjects with high cognitive control. This difference between groups should be particularly accentuated in trials where the subjects face previously unfair opponents, due to the highest need for cognitive control in terms of the inhibition of revenge seeking behavior.

Methods

Subjects

Subjects with high- vs. low cognitive control were screened via online questionnaires to assess demographic data, potential exclusion criteria, and impulsivity scores using the impulsivity scale of the adult ADHD self-report scale (ASRS; Kessler et al., 2005). (ASRS; Kessler et al., 2005). Exclusion criteria were: chronic or acute diseases which can influence the cerebral metabolism (moderate or severe craniocerebral trauma, kidney insufficiency, diabetes, unattended hypertension) or acute endangerment of self or others. Additionally, they were asked if they were in present or past under medical treatment because of neurological or psychiatric illness or if they took any (illegal) drugs the last month. In case of uncertainty regarding this question there was a free-text field where potential subjects were able to indicate potential problems. Subjects with scores between 15 and 23 on the ASRS were assigned to the high impulsivity group (=low cognitive control); subjects with scores lower than 10 were assigned to the low impulsivity group (=high cognitive control). This study was approved by the ethics committee of the Medical Faculty of the University of Tübingen and was in accordance with the current version of the Declaration of Helsinki. Written informed consent was obtained from all participants.

In total, 67 subjects participated. 29 were assigned to the low impulsive subjects group, 38 to the highly impulsive subjects group. The mean age was 34.4 years (SD=2.95), 50 participants were females, 17 males. Considering age and sex no significant differences were observed ($t(65)=1.11$, $p=.271$; $\chi^2=.592$, $p=.442$).

Experimental process

After arriving and signing the written informed consent form, the fNIRS probeset was mounted and the experiment started with the UG which was directly followed by the DG. Other tasks, which were part of a different study and will be reported elsewhere, followed approximately 30 minutes after the DG. In the end, an emotional Stroop task (Williams, Mathews, & MacLeod, 1996) was run to further assess cognitive control capacities as well as emotionality.

Paradigm

The paradigm was adapted from Brüne et al. (2013) and consisted of two subsequent tasks, an UG followed by a DG. Every game consisted of 40 trials in total and had a duration of approx. 9 minutes.

First, an UG was played against four virtual opponents. During each trial, the opponent split up 10 Euro (virtual money, 10 trials per opponent, randomized order) between themselves and the subject. The participants had the choice to accept or to reject the offer. In case of a rejection, neither the subject nor the opponent received any money. Therefore, a rejection was also an option to punish unfair offers made by the opponents. During this task, the subjects implicitly learned that there are two fair (one male, one female; offers between 3 and 5 Euro) and two unfair opponents (offers between 0 and 2 Euro). The classification of fair and unfair offers was made based on previous studies (e.g. Brüne et al., 2013; Sanfey et al., 2003). Every trial began with the presentation of the name and face of the opponent for 3 seconds, which was followed by a jittered 2–3 seconds anticipation period. After that, subjects were presented with the offer of the opponent for 3 seconds. During this decision period, the subjects had to indicate their response (acceptance vs. rejection) via button press. After that, a feedback screen was presented for 3 seconds. An inter-trial interval of jittered 2–3 seconds followed subsequently.

After the completion of the UG, a DG was played. Here, the roles changed, and the participants had to split up the money. The opponents (now the recipients) were the persons introduced in the previous UG. As in the UG, 40 trials – 10 per opponent – were played. An important difference compared to the previously played UG is that the opponents had no possibility to reject the offers made by the participants (which clearly reduces the fear of punishment for unfair money allocations). The timing and order were (beside the no choice circumstance) the same as in the UG. In both games the participants had the instruction to imagine that they were playing for real money and with real persons (with the aim to increase the involvement of the participants). As we used computer opponents with pictures taken from the study of Brüne et al. (2013), the participants were not familiar with the four different characters of the game before the ultimatum- and dictator game. In both paradigms the participants were seated in front of an Eizo® 22-inch screen, with a distance of approximately 60 cm. Only participants with normal or corrected visual capabilities were included.

Emotional Stroop task

Cognitive control and affective state were measured with an emotional Stroop task (Watts et al., 1986). Based on the stimuli of Smith and Waterman (2003), the task consisted of negative, positive and neutral words (10 stimuli per category). These 30 words were presented in 4 different colors (blue, green, red, yellow), resulting in 120 different stimuli, which were presented in the center of a black screen. The responses were assessed via a button box with one button per color. As a reminder, a button-color-assignment was presented during the whole experiment. In the beginning, 20 training trials with a correct/incorrect feedback were run. Subsequently, the experiment started with a fixation cross for 200 ms, followed by a target stimulus until response (timeout after 1000 ms). In the experimental trials no feedback was presented. Between the trials, a jittered break of 4000 to 7000 ms appeared (M. Plichta et al., 2007).

fNIRS

To assess cortical activation of the DLPFC during the DG, fNIRS was used. Biological tissue (e.g. skin or bones) is relatively transparent for near-infrared light, and oxygenated (O_2Hb) and deoxygenated (HHb) hemoglobin absorb near-infrared light with different absorption spectra (A. Fallgatter et al., 2004; Haeussinger et al., 2011). Due to these preconditions, it is possible to measure relative changes in O_2Hb and HHb in the upper 2 to 3 cm of the cortex. Based on the principle of neurovascular coupling, a decrease of HHb and an increase in the concentration of O_2Hb indicate cortical activation within a specific brain region. The measurements for this study were run with a commercial multi-channel fNIRS system (ETG-4000 Optical Topography System; Hitachi Medical Co., Japan) with a temporal resolution of 10 Hz. A 3 x 11 probeset with 52 channels (16 detectors, 17 emitters, inter-optode distance of 3 cm) was oriented on reference point Fpz and T3/T4 based on the international 10-20 system (Jasper, 1958a).

Questionnaires

In addition to the questionnaires for the screening of suitable participants, forgiveness and cognitive control-related variables were assessed. These questionnaires were completed online via Sosci Survey (D. Leiner, 2018) within one week before the measurement. The following questionnaires were used: Beck Depression Inventory (BDI; Beck, Steer, & Brown, 1996a), Tendency to Forgiveness Scale (Brown, 2003) and the Willingness to Forgive Scale (M Allemand et al., 2008). After the experiment, the desire for revenge and sympathy perception (0 to 5, 0 = low feelings of sympathy/revenge) of the participants towards their opponents was additionally assessed.

Statistical processing (behavioral data)

For testing the hypothesis of an interaction effect of fairness of the opponent (fair vs. unfair) and group of the subject (high vs. low cognitive control), a non-parametrical permutation test was used for the analysis of money allocation during the DG due to none normally distributed data. Firstly, with a permutation test for repeated measurements the differences between the offers towards fair vs. unfair opponents were analyzed. Secondly, the difference between $\text{offers}_{\text{(towards fair opponents)}}$ and $\text{offers}_{\text{(towards unfair opponents)}}$ was compared between the groups by the comparison of difference scores (ΔfairOpponent-unfairOpponent) with the same test method (see e.g. Gibbons & Chakraborti, 2011). For all analyses, MATLAB 2015b (The MathWorks, Natick, MA, USA) or SPSS 22 (SPSS Inc., Chicago, USA) were used.

Statistical processing (fNIRS data)

All fNIRS data was exported without any pre-processing. For all following analyses, MATLAB 2017 (The MathWorks, Natick, MA, USA) was used. All frequencies <0.01 Hz and >0.5 Hz were excluded with a bandpass filter. For the correction of motion artefacts, the correlation based signal improvement (cbsi) procedure of Cui et al. (2010) was used, and the resultant cbsi-hb was used for all subsequent analyses. Additionally, an Independent Component Analysis (ICA; Delorme & Makeig, 2004) was applied to exclude high amplitude artefacts. The left and the right DLPFC were defined as regions of interest (ROIs); the allocation of NIRS channels to these ROIs was made in accordance with Tsuzuki et al. (2007), Singh et al. (2005) and Rorden and Brett (2000). The positions of the ROIs are depicted in figure 1. Afterwards, the mean activation of the ROIs was extracted for further analyses. First, a 2x2 ANOVA with the within-subjects factor opponent (fair vs. unfair) and the between-subjects factor group (highly vs. low impulsive) was run, separately for each ROI. As post hoc tests, t-tests were used. For a better comparability, the fNIRS data was *z* transformed. The factor money allocation was not included because of different frequencies in the different conditions/groups. For example, the combination “unfair offer towards a previously fair opponent” was absent. Especially in the response towards unfair opponents, the frequency of fair vs. unfair offers was so different between the groups that a comparison of the fNIRS data did not seem to make much sense. Additionally, with the combined analysis of all trials (independent of the exact money allocation), statistical power was increased and we were able to investigate the mechanisms underlying behavioral differences between the groups.

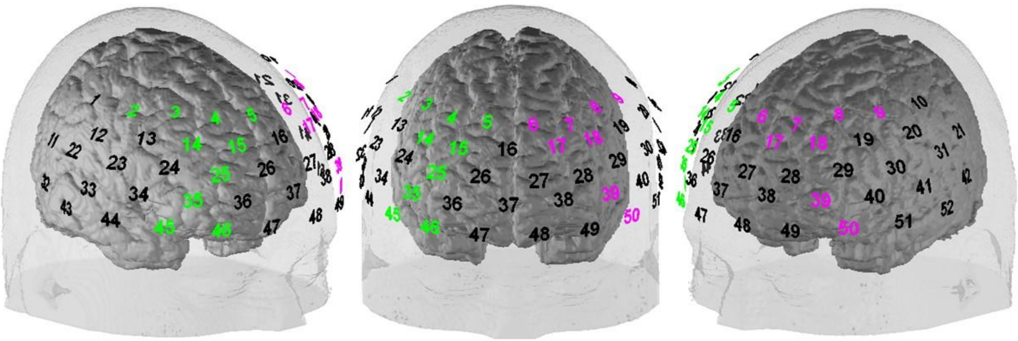

Figure 1: fNIRS probeset position. Green numbers indicate the right DLPFC, pink numbers indicate the left DLPFC.

Statistical processing (Stroop data)

For analysis of the Stroop data, the inversed efficiency score ($IES = \frac{RT}{1 - Proportion\ of\ errors}$; Townsend and Ashby (1983)) was used. Trials with more than 2 standard deviations difference from the mean per person (in total 3.72%) and incorrect trials were excluded from the analyses. After an ANOVA where no effect for stimulus valence was found, the data was merged for valence and the difference between the groups was assessed with a t-test for independent measurements.

Statistical processing (correlations)

To analyze potential brain-behavior correlations, the frequency of fair responses towards unfair opponents was calculated (=forgiveness behavior). Subsequently, this frequency was correlated (Pearson method) to the event related average (ERA) of the left DLPFC (referring to the fNIRS results) for the trials with fair and with unfair opponents. The α-value was adjusted for multiple testing with the Bonferroni method (Dunnett, 1955).

Statistical processing (logistic regression analysis)

To further analyze the results, a logistic regression separated for the groups (low vs. high impulsive) was run. The dependent variable was the number of fair offers (fair offers were defined as offer ≥ 3 € (cf. Brüne et al., 2013)) towards unfair opponents (=frequency of forgiveness); independent variables were the activation in the right and left DLPFC in trials with unfair opponents, the IES, the scores of the Tendency to Forgiveness Scale and Willingness to forgive Scale and the scores of the revenge and sympathy feelings of the participants towards unfair opponents.

Results

Stroop task and DG behavioral results

In line with our hypothesis, the highly impulsive subject group had a significantly higher IES score (indicative of lower cognitive control) than the low impulsive subject group ($t(53)=-2.53$, $p=.014$; $M_{\text{highly impulsive}} = 724.08$ vs. $M_{\text{low impulsive}} = 650.89$).

As expected, for the behavior in the DG (mean amount of allocated money) towards previously fair opponents, no effect was found ($p>.05$; $\text{Mean}_{\text{low\_impulsive}}=4.08$ € ($SD=0.96$), $\text{Mean}_{\text{highly\_impulsive}} =3.86$ € ($SD=0.99$)). Towards unfair opponents, a significant difference between the groups was found ($p<.05$; $\text{Mean}_{\text{low\_impulsive}}=2.86$ € ($SD=1.21$), $\text{Mean}_{\text{highly\_impulsive}} =2.20$ € ($SD=1.24$)). Permutation tests for the double contrast (highly impulsive vs. low impulsive for fair vs. unfair opponents) furthermore indicate a significant interaction between both factors (group × opponent) ($p<.05$, $\Delta_{\text{low\_impulsive(fairOpponent-unfairOpponent)}}=1.22$ € ($SD=0.88$) vs. $\Delta_{\text{highly\_impulsive(fairOpponent-unfairOpponent)}}=1.65$ € ($SD=0.97$)). Figure 2 depicts the probability density function estimate separately for group and opponent.

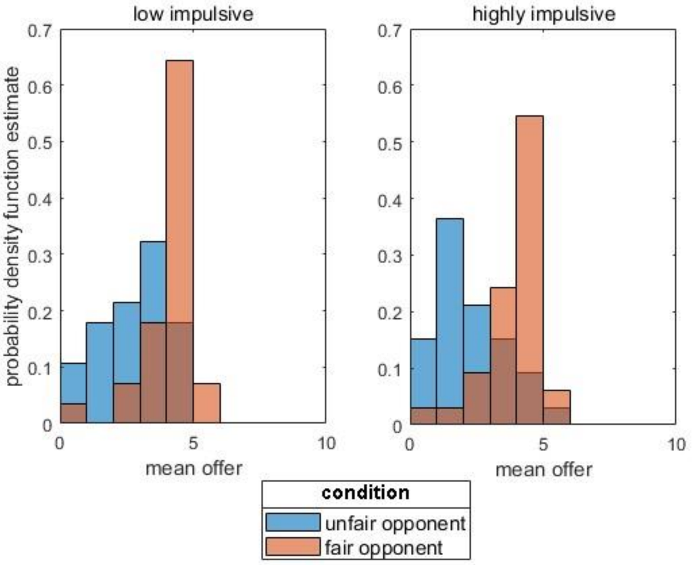

Figure 2: Probability function estimate for low vs. high impulsive subjects for the mean offers (in €) separated for unfair (blue columns) vs. fair (orange columns) opponents.

Questionnaire results

For the results of the questionnaires and group comparisons, see Table 1. In a t-test for unrelated measurements, a significantly higher mean BDI was found in the highly impulsive group. Additionally, a significantly higher desire for revenge towards unfair opponents was found in this group. In the low impulsive group, a marginally higher feeling of sympathy was found.

Table 1: Results of the different questionnaires separated for groups.

Questionnaire	Low impulsive group (23 female, 6 male) (*M*, *SD*)	Highly impulsive group (27 female, 11 male) (*M*, *SD*)	*t*-value, *p*-value (one-tailed)
BDI	4.44, 3.13	9.60, 7.07	-4.00, <.001*
Tendency to Forgiveness Scale	15.25, 4.15	14.48, 4.67	0.68, 0.245
Willingness to forgive Scale	20.96, 5.12	21.21, 5.04	-0.19, 0.423
Desire for revenge (towards unfair opponents)	2.67, 0.99	3.13, 1.03	-1.79, 0.035*
Feelings of sympathy (towards unfair opponents)	2.10, 0.53	1.90, 0.59	1.43, 0.075

* significant group difference (*p*<0.05)

fNIRS results

We ran a 2x2 ANOVA with the within-subjects factors opponent (fair vs. unfair) and the between-subjects factor group (highly vs. low impulsive) separated for the left and the right DLPFC. We found no effect in the right DLPFC. In the left DLPFC, a main effect for opponent (*F*(1, 65)= 4.53, *p*=.037) and an interaction effect of group and opponent was found (*F*(1, 65)= 4.28, *p*=.042). Subsequently, a post-hoc t-test for repeated measurements was run separately for groups. No significant differences between fair and unfair opponents occurred in the low-impulsive group (*t*(37)=0.51, *p*=.960). However, in highly-impulsive subjects a significant difference between trials with fair vs. unfair opponents was found (*t*(28)=2.40, *p*=.023), with higher hemodynamic responses in the left DLPFC during money allocation to unfair opponents. These effects are depicted in figure 3.

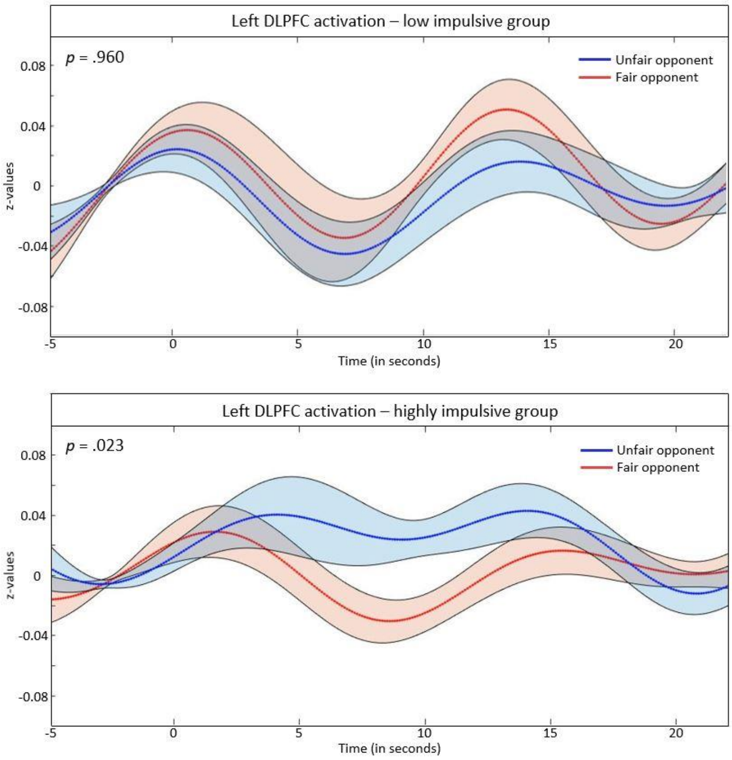

Figure 3: z-values of the ERA signal in the left DLPFC separated for the low and highly impulsive group. The shaded parts indicate the standard error of the mean.

Correlational results

In the highly impulsive group, no significant correlations were found. In contrast, the low impulsive group showed a significant negative correlation (*r*=-.499, *p*=.018) between activation in the left DLPFC and the frequency of fair offers towards unfair opponents (=forgiveness behavior).

Regression analyses

For the low impulsive group, only the perceived sympathy of the unfair opponent had a significant influence on the response towards unfair opponents (*F*(1, 22)=7.36, *p*=.013, *n*=23). With one point more in the sympathy rating (sympathy feelings towards unfair opponents), the low impulsive subjects allocated on average 1.068 € more to unfair opponents. For the highly impulsive subjects, only the perceived revenge feeling towards unfair opponents had a significant influence on their money allocation towards unfair opponents (*F*(1, 21)=6.85, *p*=.016, *n*=22). With one point more in the revenge rating (revenge feelings towards the unfair opponents), the highly impulsive subjects allocated on average 4.096 € less to the unfair opponents.

Discussion

This study investigated the effects of cognitive control mechanisms on forgiveness towards unfair opponents in a combined ultimatum/dictator game. The results of the emotional Stroop task confirmed the expected lower cognitive control capacity of the highly impulsive group. Towards previously unfair opponents (where forgiveness is necessary for a fair response), a significant difference between the groups was observed. As hypothesized, the highly impulsive group showed significantly less forgiveness/more revenge behavior. According to our hypotheses, we found no behavioral differences between groups towards previously fair opponents (control condition).

We also hypothesized that higher rates of forgiveness in the low impulsive group would be accompanied with higher activity in the right DLPFC, comparable to other results in this field (e.g. Brüne et al., 2013; Maier et al., 2018). Surprisingly, we found no activation differences between fair and unfair opponents in the low impulsive group, and no group difference regarding the activation of the right DLPFC. In the left DLPFC, highly impulsive subjects exhibited significantly higher activation when playing against unfair opponents as compared to fair opponents. As it is assumed that cognitive control is needed to forgive (e.g. Pronk et al., 2010), and the left DLPFC is generally seen as a cognitive control region (e.g. M. M. Botvinick et al., 2001; Egner & Hirsch, 2005b), this finding only in the highly impulsive group (which was less forgiving) is unexpected. To further analyze these unforeseen results, we ran a multiple regression analysis to explore the mechanisms underlying the different behavioral patterns in the low vs. highly impulsive group. While in low impulsive subjects only perceived sympathy for their virtual (unfair) opponents predicted money allocation, in the highly impulsive group revenge feelings significantly predicted the behavior. One explanation for the increased activation in the left DLPFC in highly impulsive subjects during money allocation to unfair opponents might therefore lie within this revenge motivation. In a study of Strobel et al. (2011), higher activation in the left DLPFC was observed during a DG with the option for punishment. In line with this, Ricciardi et al. (2013a) found higher left DLPFC activation during taking revenge in comparison to forgiving during social scenario evaluations. The stronger revenge driven behavior of the highly impulsive subject group is very well in line with the results of Jones and Paulhus (2011) who also found more pronounced psychopathy and narcissism scores in persons with high impulsivity scores.

The fact that the low impulsivity group unexpectedly did not show increased activation in cognitive control areas despite displaying more pronounced forgiveness behavior might be explained by the specificities of the low impulsive control group. It is assumed that cognitive control is needed to forgive due to the necessary suppression of unwanted (e.g. revenge seeking) emotional feelings (Maier et al., 2018; Wilkowski et al., 2010). James and Taylor (2007) found that impulsivity is positively correlated with negative emotionality. This is well in line with the significantly lower desire for revenge in the low impulsive group also after unfair treatment, which may have led to a reduced need to suppress unwanted revenge seeking feelings via mechanisms of cognitive control. To summarize, the unexpected lack of significant activation in cognitive control areas (i.e., DLPFC) in the low impulsive group could be explained by the fact that these subjects did not have any unwanted emotions to suppress, whereas the highly impulsive subjects were primarily revenge-driven in their behavior.

Alternatively, the unfair behavior of the highly impulsive group could also be interpreted as a more controlled and economically elaborated behavior, since allocating a small (“unfair”) amount of money makes sense from an economical perspective (e.g. Fehr & Fischbacher, 2004b), depending on one’s motivational attitude. The higher activation in the left DLPFC as part of the cognitive control network could reflect this elaborated and cognitively controlled behavior. However, this interpretation would be contradictory to the results of the emotional Stroop task and previous findings on the connection between impulsivity and (low) cognitive control (e.g. Ehlis et al., 2008; Fallgatter et al., 2005; Herrmann et al., 2010) and is therefore rather implausible.

Attention should also payed to the fact that the highly impulsive group indicated significantly higher values in the BDI. All subjects were far away from a pathological threshold (only subjects without psychiatric disorders were invited), nevertheless in the literature depression is linked with lower abilities to forgive (Hirsch, Webb, & Jeglic, 2011; Tse & Cheng, 2006). But keeping the ecological validity in mind and the strong connection between the concepts of impulsivity and depression an avoidance of these differences would not be useful.

In future studies also other brain regions like the posterior parietal cortex should be studied, as this brain region is in combination with the DLPFC known as part of the central executive network (Rosenbaum, Hilsendegen, Thomas, Haeussinger, Metzger, et al., 2018; Sridharan, Levitin, & Menon, 2008). This network is inter alia responsible for social cognition which plays a crucial role in forgiveness processes (Sherman et al., 2014). More knowledge about the underlying network mechanisms would help to understand the neural foundations of forgiveness processes to a new extend. Also other brain areas like the ACC and the IFG, which are known to play a role in forgiveness processes, could be investigated regarding their role in prosocial behavior in future studies.

In the present study there was an imbalance between male and female participants. This difference was caused in the difficulty to recruit the same number of male and female participants who met the very specific inclusion criteria. Nevertheless, it is known that the gender can have an influence on forgiveness processes, as woman are known to show more forgiveness behavior than men (Shackelford et al., 2002; Wade & Goldman, 2006). For the further investigation of the neural foundations of these differences in future studies a gender balance should be aimed.

Another potentially critical point of the present study are the various approaches used to analyze the results of the behavior in the dictator game and the emotional Stroop task and the neural activation differences between the groups. Due to the different research questions targeted in this study with different tasks and approaches it was not possible to limit the statistical analyses to one specific test. Therefore, keeping a potential power inflection in mind, the results have to be interpreted with some caution, even if the discussed results seem to be robust.

In conclusion, the results of this study provide new insights into the impact of impulsivity on forgiveness behavior and underlying mechanisms of cognitive control. First, the behavioral data indicate a difference in the ability and/or willingness to forgive between low vs. highly impulsive subjects. Secondly, regression analyses and the fNIRS data indicate that these differences in retaliation are possibly based on diffent motivations: While the behavior of the low impulsive group could mainly be associated with sympathy, the behavior of highly impulsive subjects might have been determined by feelings of revenge. Keeping the fundamental importance of reconciliation for health (Friedberg et al., 2007), coping with stress (Worthington et al., 2007) and overall mortality (L. L. Toussaint et al., 2012) in mind, the data in this study provide relevant insights into mechanisms underlying reduced forgiveness behavior in highly-impulsive subjects, with possible clinical implications, for example, for patients with ADHD, addiction or personality disorders.

Funding

This study was supported by the German Research Foundation (Deutsche Forschungsgemeinschaft [DFG] project number EH 388/2-1). Ann-Christine Ehlis was partly supported by IZKF Tübingen (Junior Research Group, grant 2115-0-0). We acknowledge support by Open Access Publishing Fund of University of Tübingen.

Acknowledgements

We would like to thank Björn Enzi for sharing the presentation file for running the paradigm and Ramona Täglich, Alexander Krieg, Hendrik Laicher and Julian Schiel for their valuable support with collecting the data and Nora Güthlein for her great assistance with correcting the fNIRS data.

Conflict of Interest Statement

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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7.4. STUDY 4: THE IMPACT OF TMS-ENHANCED COGNITIVE CONTROL ON FORGIVENESS PROCESSES

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Under review

Abstract

It is assumed that cognitive control is needed for forgiveness processes. For investigating this connection, highly impulsive subjects, who oftentimes fail in inhibiting revenge feelings, received an activating theta-burst stimulation (TBS) of the right dorsolateral prefrontal cortex (rDLPFC), a classical cognitive control region. For testing the ability to forgive, the subjects were tested in a randomized, double-blinded, within-subjects design, in which they received verum TBS versus sham TBS. In both sessions, they first learned in an ultimatum game that there are fair and unfair opponents and subsequently played a dictator game with reversed roles with the opportunity to take revenge or forgive their opponents from the previous game. Against our hypotheses, the activating TBS did not increase the forgiveness behavior towards unfair opponents. However, it increased the generosity towards previously fair opponents. As a potential explanation, it is discussed that the TBS was only able to influence the 'cold' emotion greed but not 'hot' emotions such as anger.

Keywords: *Revenge, Cognitive Control, fNIRS, TMS, Emotion Regulation*

Introduction

The ability to forgive others for their misdemeanors is highly relevant for cooperation and reciprocality (Trivers, 1971). Moreover, individuals with better abilities to forgive show higher rates of wellbeing (Worthington et al., 2007), better cardiovascular health (Friedberg et al., 2007), better quality of relationships (Mathias Allemand, Amberg, Zimprich, & Fincham, 2007) and lower mortality (L. L. Toussaint et al., 2012), suggesting that forgiveness is beneficial to many areas of life.

Approaches to define forgiveness have focused on different elements involved in the process of forgiving (McCullough, 2001; Riek & Mania, 2012). For example, McCullough, Worthington Jr, and Rachal (1997) define forgiveness mainly as a change in motivation away from avoiding contact with the transgressor and revenge-seeking to more reconciliatory behavior. Along similar lines, Worthington Jr and Wade (1999) render forgiveness as the replacement of negative emotions with positive emotions towards the offender. Finally, Wilkowski et al. (2010) describe forgiveness as a two-step process combining (1) the decision to forgive and (2) inhibiting revenge, suggesting a pivotal role of cognitive control in acting in forgiving ways.

Cognitive control as a neuropsychological concept consists of three subfunctions: task-switching, updating and inhibition (Miyake et al., 2000). Generally, cognitive control is a highly relevant function for nearly all areas of life including academic or financial success (Moffitt et al., 2011). Conversely a lack of cognitive control is associated with various mental disorders (e.g. Barth et al., 2015; Ehlis et al., 2008; Fallgatter et al., 2005; Rosenbaum, Thomas, et al., 2018).

At the neuronal level, neuroimaging studies have shown that response conflicts – requiring increased levels of cognitive control – are associated with increased activity of the anterior cingulate cortex (ACC). This internal monitoring system “reports” potential conflicts that inhibit prepotent, automatic responses to the dorsolateral prefrontal cortex (DLPFC) which subsequently implements cognitive control to resolve the response conflict ("conflict monitoring theory"; M. Botvinick, T. S. Braver, et al., 2001; Botvinick et al., 2004b; Egner & Hirsch, 2005b; MacDonald et al., 2000; M. Milham et al., 2001). To investigate the connection between forgiveness processes and activation of the DLPFC, Brüne et al. (2013) combined an ultimatum game and a dictator game in an fMRI study. First, the participants played an ultimatum game in which the subjects had to accept or reject fair or unfair offers made by the opponents who had to split up 10 Euro in every trial. During this game, the subjects implicitly learned that there are fair (offers between € 3 and 5) und unfair (offers between € 0 and 2) opponents. Afterwards, the roles changed, and the subjects had to split up the money in a dictator game. Here, the subjects had the possibility to take revenge by allocating an unfair amount to the unfair opponents or to forgive by allocating a fair amount of money. Interestingly, forgiveness behavior was associated with a higher activation in the right DLPFC, which is compatible with the conflict monitoring theory outlined above. To further investigate this connection, Maier et al. (2018) combined the gaming paradigm of Brüne et al. (2013) with inhibitory continuous theta burst stimulation (cTBS; Huang et al., 2005) of the right DLPFC. With cTBS the activation of a specific brain area can be reduced for a certain time (Huang et al., 2005). According to the conflict monitoring theory and the results of Brüne et al. (2013), lower rates of forgiveness were found with a reduced activity in the right DLPFC (compared to placebo condition involving sham stimulation). Based on these findings – which suggest a causal involvement of the right DLPFC in forgiveness processes – the question arises if a targeted *increase* in activation of the right DLPFC (induced by transcranial magnetic stimulation (TMS)) could also influence forgiveness processes (in the opposite direction; that is, increase forgiveness).

Since impulsivity is negatively correlated with cognitive control, one could argue that highly impulsive individuals might benefit from a stimulation of the right DLPFC by gaining more cognitive control over their prepotent emotional responses to unfairness. This may also be clinically relevant, because impulsivity and poor inhibitory control are associated with various mental disorders such as ADHD or Borderline personality disorder (Bari & Robbins, 2013; Christodoulou, Lewis, Ploubidis, & Frangou, 2006; Ehlis et al., 2008; Herrmann et al., 2009). Accordingly, we sought to study the effect of intermittent TBS (iTBS; Huang et al., 2005) over the right DLPFC in a highly impulsive group of subjects on forgiveness behavior. iTBS has the potential to increase the neuronal activity in the targeted brain area for at least 15 minutes (Huang et al., 2005). Here, we applied iTBS in a within-subject-design, a double-blind placebo controlled experiment in randomized order. To control for the stimulation effect and investigate the underlying neuronal processes, functional near-infrared spectroscopy (fNIRS) over the DLPFC was applied.

We specifically hypothesized that the stimulation of the right DLPFC would increase forgiveness behavior by improving cognitive control and reduce the effect of prepotent impulsive emotional responses. Moreover, we expected an increase in activation in the right DLPFC (as assessed via fNIRS) in the verum condition compared to placebo.

Methods

Subjects

The subjects were recruited via a university wide circular email. This email included a link to the impulsivity scale of the Adult ADHD self-report scale (ASRS; Kessler et al., 2005). Only subjects with scores between 15 and 30 in this questionnaire were contacted for this study. Further exclusion criteria were chronic or acute diseases which can potentially influence the cerebral metabolism (craniocerebral trauma, kidney failure, diabetes, uncontrolled hypertension), neurological or psychiatric illnesses (present or past), acute endangerment of self or others and any contraindications for TMS (see Rossi et al., 2009). In total, 30 subjects participated in this study, all of which were students at the University of Tübingen. The average age was 23.75 years (SD=3.05); 5 subjects were male. For their participation, subjects received a financial compensation of 10 Euro per hour. The study was in accordance with the current version of the Declaration of Helsinki and was approved by the ethics committee of the Medical Faculty of the University of Tübingen. Written informed consent was obtained from all subjects. The scores of the different questionnaire scores are described in table 1.

Table 1: Questionnaire scores of the study sample

Questionnaire	**Mean**	**SD**
ASRS	20.41	5.29
BDI	5.86	5.61
Willingness to forgive	21.20	4.34
Tendency for Forgiveness	14.36	4.24

Adult ADHD self-report scale (ASRS; Impulsivity Scale; Kessler et al., 2005), Beck Depression Inventory (BDI; Beck et al., 1996a), Willingness to Forgive Scale (M Allemand et al., 2008), Tendency to Forgive Scale (Brown, 2003).

Paradigm

The paradigm was adapted from the studies of Brüne et al. (2013) and Maier et al. (2018). It consisted of two consecutive tasks, an Ultimatum Game followed by a Dictator Game. Each game involved 40 trials and had a duration of approximately 9 minutes. In the Ultimatum Game the participants first were presented with a picture and the name of the opponent in the trial for 3 seconds. Following the presentation of the current opponent, a jittered break with a fixation cross followed for 2–3 seconds. After this, the offer of the current opponent was presented to the participant. Fictional 10 Euro were split up on every trial by a total of 4 opponents: 2 unfair (1 male, 1 female; offers between 0 and 2 Euro) and 2 fair (1 male, 1 female; offers between 3 and 5 Euro; cf. Brüne et al., 2013; Sanfey et al., 2003). After the decision of the participant to accept or reject the offer (via button press), a feedback screen was shown for 3 seconds with the money allocations. If the subject rejected an offer, the opponent also received 0 Euro. In this game, the participants implicitly learned that there are fair and unfair opponents. After finishing the Ultimatum Game, the subjects received the cTBS (described below) in a separate room and started the Dictator Game – after fitting the fNIRS cap – approximately 8 minutes after finishing the Ultimatum Game. All timing issues were the same in the Dictator Game and in the Ultimatum Game. Only the roles changed, so now the subjects had to split up fictional 10 Euro in every trial towards the opponents from the previous game. An important difference to note is that in this game the opponents had no possibility to reject an offer made by the participants. Therefore, in this game the participants had the chance to forgive (with allocating a fair amount of money) or to take revenge (with allocating an unfair amount of money) on their unfair opponents. In the whole paradigm, the participants were instructed to imagine that they were playing for real money and with real persons. The "Presentation" software-package (Neurobehavioral Systems Inc., Albany, CA, USA) was used for presenting the experiment.

Intermittent Theta Burst Stimulation (iTBS)

The iTBS was applied at electrode position F4 (Herwig et al., 2003) over the right DLPFC using the iTBS protocol of Huang et al. (2005). Generally, iTBS shows lasting effects for at least 15 minutes after a stimulation of 3 minutes and 10 seconds. The following protocol was used: a 2 s train of 3 impulses given at 50 Hz was repeated every 10 s for 190 s (600 pulses in total). The impulses were given at 80% individual motor threshold. With the active-passive placebo/verum coil system by MagVenture® all stimulations were applied in a double-blind fashion. In order to ensure similar subjective sensations in both sessions, the placebo sessions were masked with electrodes at the stimulated head area inducing a feeling comparable to the verum protocol. The experimenter received only a numerical blinded code to start the sessions. For reducing any further expectancy effects, all measurements were run by two experimenters; one experimenter only performed the stimulation and had nearly no conversation with the subject, the other experimenter ran the experiments and was in another room during the stimulation. After arranging the fNIRS cap for approximately 5 minutes, the DG and the fNIRS measurement began.

fNIRS

The cortical activation of the participants during the DG was measured with fNIRS. Due to the relative transparency of biological tissue for near-infrared light and the different absorption spectra of oxygenated (O2Hb) and deoxygenated (HHb) for near-infrared light (A. J. Fallgatter, A. C. Ehlis, A. Wagener, T. Michel, & M. Herrmann, 2004; Haeussinger et al., 2011), it is possible to measure cortical activation through the intact skull. An increase in the concentration of O2Hb and a decrease of HHb indicates cortical activation within the measured brain region. In this study, a commercial multi-channel NIRS system (ETG-4000 Optical Topography System; Hitachi Medical Co., Japan) with a temporal resolution of 10 Hz was used. The 3 x 11 probeset with 52 channels, comprising 16 detectors and 17 emitters with an inter-optode distance of 3 cm, was placed according to the international 10-20 system for electrode placement (Jasper, 1958a). The central optode of the bottom row was placed on Fpz and the bottom row was symmetrically orientated towards T3/T4.

Questionnaires

In addition to the screening questionnaire, forgiveness and cognitive control related variables were assessed via Sosci Survey (D. Leiner, 2018) within one week before the first measurement. The following questionnaires were included: Beck Depression Inventory (BDI; Beck et al., 1996a), Tendency to Forgiveness Scale (6 statements about forgiveness in general, participants rate their concurrance; Brown, 2003) and the Willingness to Forgive Scale (12 scenarios which include a variety of transgressions and the assesment of the likelihood to forgive; M Allemand et al., 2008). In both sessions, after the DG the desire for revenge, sympathy and perceived fairness (0 to 5, 5=high feelings of revenge/sympathy/fairness) of the participants towards the opponents was assessed.

Analyses

Behavioral data

For the analyses of the behavioral data, the median of scores was used. We decided to take the median as this parameter represents the central value of the data and is less vulnerable to outliers. Since there was no normal distribution of the values, the non-parametrical Wilcoxon test (Gehan, 1965) was used. For assessing a potential interaction effect, first the difference scores ($\text{median}_{\text{fair\_opponent}}$ - $\text{median}_{\text{unfair\_opponent}}$) of the placebo and the verum condition were tested with a Wilcoxon test. Subsequently – as post-hoc tests – two additional Wilcoxon tests were calculated, the median offer in the placebo vs. verum condition towards unfair opponents and the median offer in the placebo vs. verum condition towards fair opponents. As effect size we used Cohen's *d* (Cohen, 1988).

fNIRS data

The fNIRS data was exported without prior preprocessing; all analyses were run with MATLAB 2017 (The MathWorks, Natick, MA, USA). All frequencies <0.01 Hz and >0.5 Hz were excluded with a bandpass filter. Additionally, the correlation based signal improvement procedure (CBSI; Cui et al., 2010) was used for correcting motion artefacts. Any further analyses were run with the resultant cbsi-hb. For excluding residual artifacts, an independent component analysis (ICA; Delorme & Makeig, 2004) was used. A model-based analysis for event-related fNIRS data (M. M. Plichta, S. Heinzel, A.-C. Ehlis, P. Pauli, & A. J. Fallgatter, 2007) was used after the pre-processing of the data. The resulting ß values were used for all further tests, which were run using SPSS 22 (SPSS Inc., Chicago, USA).

Reaction time

The reaction times of the money allocations were analyzed using a 2x2 ANOVA with the within-subjects factors condition (verum vs. placebo) and opponent (fair vs. unfair). All trials with more than two standard deviation difference from the mean per person were excluded from the analyses. All analyses were run using SPSS 22 (SPSS Inc., Chicago, USA).

Results

Behavioral results

In the Wilcoxon test of the difference scores (allocated amount of money; $\text{median}_{\text{fair\_opponent}}$ - $\text{median}_{\text{unfair\_opponent}}$), a significant difference was found between the placebo and verum condition ($z=-2.046$, $p=.041$, $n=30$, $r=.37$). This interaction effect is depicted in figure 1. Contrary to our hypothesis that the subjects in the verum condition would be more generous towards unfair opponents, we found no differences between the conditions ($z=-0.941$, $p=.361$, $n=30$, $r=.16$).

Surprisingly, towards fair opponents, we found a significant difference between the stimulation conditions (z=-2,154, p=.031, n=30, r=.39) with a higher median after verum (M=4.016, SD=1.262) compared to sham stimulation (M=3.750, SD=1.489).

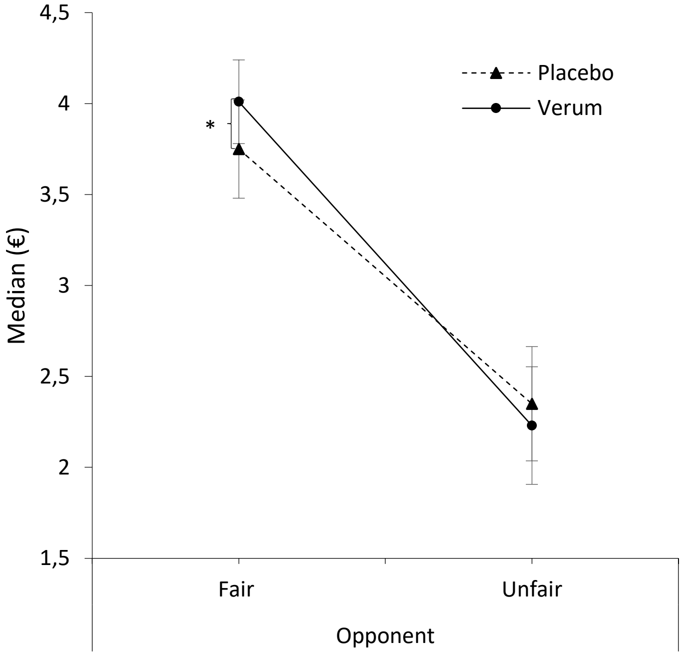

Figure 1: Mean median offer of the subjects in the verum vs. placebo condition towards fair vs. unfair opponents. The significant difference is marked with a star, the error bars indicate the standard error.

For the reaction times, in a 2x2 ANOVA, a main effect of the factor opponent was found (F(1,22)=35.81, p<.001) with significantly higher reaction times for unfair opponents (M=3050 ms, SD=450 ms) than for fair opponents (M=2907 ms, SD=509 ms).

fNIRS results

In order to assess the effect of the facilitating iTBS on the right DLPFC, brain activation in this area was assessed via fNIRS. In accordance with previous studies (Brüne et al., 2013; Maier et al., 2018), the *forgiveness* condition (with fair offers towards previously unfair opponents) was specifically investigated, as in this condition cognitive control areas (including the right DLPFC) should be most critically involved. The fNIRS data for the right DLPFC was normally distributed (p<.05) according to the Kolmogorov-Smirnov test (Massey Jr, 1951). In a t-test for trials in which forgiveness behavior was shown, the activation in the right DLPFC was significantly higher in the verum condition compared to placebo (t(33)=2.039, p=.025). In figure 2 this difference in the right DLPFC is depicted.

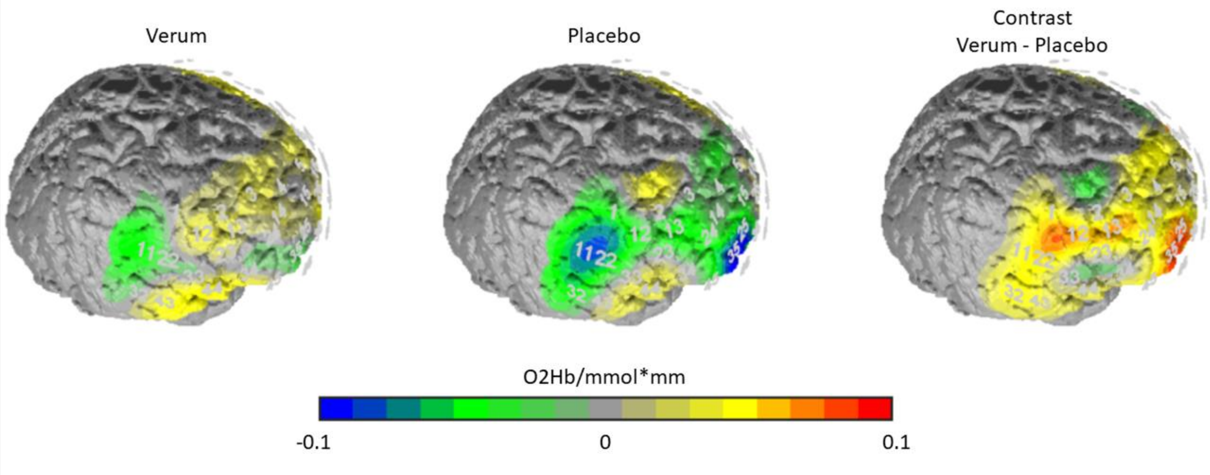

Figure 2: O2Hb/mmol*mm for the verum condition, the placebo condition and the contrast verum – placebo for trials with fair offers towards unfair opponents (= forgiveness).

Discussion

It was hypothesized that the subjects in the verum condition (increased DLPFC activity through iTBS) would act more in a socially desired way, in terms of money allocations closer to 5 Euro, as the subjects in this condition have more “resources” for applying social norms (and resisting baser emotional impulses). Especially, we expected more forgiveness behavior (fair offers towards previously unfair opponents) in the verum condition. Against our hypotheses, the subjects were not less revenge seeking/more forgiving towards previously unfair opponents in the verum condition, even though the analysis of the fNIRS data showed that the facilitating iTBS was applied successfully over the right DLPFC. A change of the behavior was found in the reaction towards previously fair opponents. Here, the subjects in the verum condition (= more activity in the right DLPFC) were more generous compared to the placebo condition.

The following paragraphs are a first attempt to interpret these surprising results. According to Seuntjens, Zeelenberg, Van de Ven, et al. (2015), impulsivity and greed are positively correlated, whereas self-control and greed are negatively correlated. In the same way, greed may be a highly relevant motive for persons with high impulsivity scores/low self-control. But this motive oftentimes conflicts with general social norms. Greed is regularly associated with negative features like selfishness, materialism, never satisfied, not generous, egocentrism, immoral behavior or arrogance (Seuntjens, Zeelenberg, Breugelmans, & Van de Ven, 2015). Therefore, this motive should be normally inhibited as far as possible; to do so, cognitive control is necessary. In the highly impulsive subjects group, in which the inhibition of unwanted emotions is normally hampered, an activation of the rDLPFC via iTBS could inhibit the greed motive. It can be assumed that greed towards fair persons is especially socially sanctioned, so that the activation of the right DLPFC has a bigger influence particularly in this condition.

It could be argued that there is a difference between trait characteristics such as greed and state emotionality such as anger about a recently happened transgression. The emotional reactions to unfairness towards oneself are described as very intense emotional feelings of anger (e.g. Civai, Corradi-Dell'Acqua, Gamer, & Rumiati, 2010; Pillutla & Murnighan, 1996). Especially in high arousal conditions, the amygdala plays a particularly crucial role (Lindquist et al., 2012). The fact that impulsivity and the experience of negative emotions are highly correlated (Boschloo et al., 2013) and related to amygdala activity (Lindquist et al., 2012) could explain why in the condition towards unfair opponents the activating TBS of the right DLPFC did not have a significant influence. Completely different is the situation towards fair opponents where no previous transgression was inducing intense, 'hot', negative emotions. Here, the concept of greed may be decisive. In the literature, it is well described that the right DLPFC is responsible for the implementation of social norms (e.g. Buckholtz, 2015; Knoch & Fehr, 2007). Regarding the results in the present study it could be argued that the increase of activity in the right DLPFC leads to a stronger implementation of the social norm of generosity (in contrast to greed) but it is not able to influence the 'hot' emotion anger which leads to revenge towards previously unfair opponents. Schaefer et al. (2003) investigated the neural location of 'hot' and 'cold' processes and found differences between them. In more schematic 'hot' processes, especially the ventromedial prefrontal was activated, whereas the anterolateral prefrontal cortex was activated in more 'cold' propositional situations. Interestingly, with our TMS coil stimulating specifically the lateral (and not the medial) prefrontal cortex, our results would fit this model and explain why 'cold' processes (related, e.g., to the implementation of social norms, such as generosity) seemed particularly affected.

For investigating the exact connections between impulsivity, cognitive control, generosity and forgiveness, further studies are necessary. In this study, only highly impulsive subjects were measured. In future studies, additionally a healthy control group should be tested. With this addition it would be possible to compare the effects of an activating TBS on subjects with different levels of greed, cognitive control and emotionality. Moreover, in future studies it would be highly interesting to investigate the role of other brain areas (e.g., the amygdala) in forgiveness processes in different subject groups.

It can be concluded that the results of this study were partly unexpected but provided interesting insights in the connection between impulsivity and the effects of TBS. According to a first interpretation of the results, the facilitating TBS of the right DLPFC was able to influence ‘cold’ emotional processes but not ‘hot’ emotions such as anger. Further research for clarifying these results is needed.

Acknowledgements

We would like to thank Björn Enzi for sharing the presentation file for running the paradigm and Ramona Täglich, Alexander Krieg and Hendrik Laicher for their valuable support with collecting the data and their great assistance with correcting the fNIRS data. This study was supported by the German Research Foundation (Deutsche Forschungsgemeinschaft [DFG] project number EH 388/2-1). Ann-Christine Ehlis was partly supported by IZKF Tübingen (Junior Research Group, grant 2115-0-0).

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ACKNOWLEDGEMENTS

Mein großer Dank gilt Dr. Ann-Christine Ehlis für die außerordentliche inhaltliche und persönliche Unterstützung in allen Phasen des Projektes und insbesondere für den Freiraum, mit dem ich eigene Forschungsideen entwickeln und verwirklichen konnte. Prof. Andreas Fallgatter danke ich ebenfalls für die Unterstützung und die Ressourcen während des Projektes sowie für das in mich gesetzte Vertrauen. Auch gilt mein Dank Prof. Martin Hautzinger und Prof. Hong Yu Wong die mich als Mitglieder meines Advisory Boards in den vergangenen drei Jahren durch die vielen spannenden Anregungen inspiriert und vorangebracht haben. Des Weiteren möchte ich Dr. Florian Häußinger für die vielen Stunden geduldigen, gemeinsamen Programmierens danken. Ohne die großartige technische Expertise von Ramona Täglich und Betti Schopp bei den zahlreichen angewandten Messmethoden wären die vielen Messungen nicht von Anfang an so reibungslos verlaufen, auch dafür möchte ich herzlich danken.

Ebenso möchte ich meinen großartigen Kolleginnen und Kollegen und dabei insbesondere meinen Büronachbarn Dr. Beatrix Barth und Dr. David Rosenbaum dafür danken, dass ich immer gerne zur Arbeit kam und dabei meist ein Lächeln auf den Lippen hatte. Meinen beiden HiWis Hendrik Laicher und Alexander Krieg danke ich für die jahrelange zuverlässige Zusammenarbeit und die Vielzahl an erfolgreich durchgeführten Messungen. Zudem möchte ich Jan Staudenmaier, Max Sonnenschein und Johannes Scherzinger für das Korrekturlesen meiner Thesis danken.

Mein Dank gilt auch Celina für die Unterstützung während der letzten Jahre und die beflügelnden Diskussionen über meine aktuellen Forschungsprojekte. Meinen Eltern danke ich dafür, dass sie mir die Freiheit und das Vertrauen dazu gegeben haben, meinen eigenen Weg zu gehen. Zuletzt möchte ich meinem Opa Egon danken, der mich schon während meiner Kindheit und Jugend an die Genauigkeit und Persistenz herangeführt hat, die für gutes wissenschaftliches Arbeiten unabdingbar sind.