Effects of transcranial direct current stimulation on risky decision making are mediated by ‘hot’ and ‘cold’ decisions, personality, and hemisphere

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Abstract

Previous results point towards a lateralization of dorsolateral prefrontal cortex (DLPFC) function in risky decision making. While the right hemisphere seems involved in inhibitory cognitive control of affective impulses, the left DLPFC is crucial in the deliberative processing of information relevant for the decision. However, a lack of empirical evidence precludes definitive conclusions. The aim of our study was to determine whether anodal transcranial direct current stimulation (tDCS) over the right DLPFC with cathodal tDCS over the IDLPFC (anodal right/cathodal left) or vice versa (anodal left/cathodal right) differentially modulates risk-taking in a task [the Columbia Card Task (CCT)] specifically engaging affect-charged (Hot CCT) vs. deliberative (Cold CCT) decision making. The facilitating effect of the anodal stimulation on neuronal activity was emphasized by the use of a small anode and a big cathode. To investigate the role of individual differences in risk-taking, participants were either smokers or non-smokers. Anodal left/cathodal right stimulation decreased risk-taking in the ‘cold’ cognition version of the task, in both groups, probably by modulating deliberative processing. In the ‘hot’ version, anodal right/cathodal left stimulation led to opposite effects in smokers and non-smokers, which might be explained by the engagement of the same inhibitory control mechanism: in smokers, improved controllability of risk-seeking impulsivity led to more conservative decisions, while inhibition of risk-aversion in non-smokers resulted in riskier choices. These results provide evidence for a hemispheric asymmetry and personality-dependent tDCS effects in risky decision making, and may be important for clinical research on addiction and depression.

Introduction

Making the right decisions in a complex environment that is full of seductive as well as frightening options requires careful weighing of risks and benefits, and a sound regulation of affective impulses. Recent evidence suggests that the prefrontal cortex (PFC) is a pivotal area for deliberative processing (Weber et al., 2004; Krawczyk, 2012; Minati et al., 2012b) as well as cognitive inhibitory control (Cohen, 2005; Ochsner & Gross, 2005; Knoch et al., 2008; Goldstein et al., 2009; Dolcos et al., 2011; Mitchell, 2011; Ridderinkhof et al., 2011).

Some neuroimaging (Ernst et al., 2002; Schonberg et al., 2012) and brain-stimulation studies (Knoch et al., 2006; Fecteau et al., 2007a) suggest that the right dorsolateral PFC (rDLPFC) may be particularly critical to exert cognitive control on affective impulses and therefore to limit the influence of affect in risky decision-making behavior in healthy participants. Observations in substance abuse disorders that are related to impaired risky decision-making behaviors (for review, see Murphy et al., 2012) further support the idea of a lateralization of DLPFC function in risky decision making (Cservenka & Nagel, 2012). Smokers, for example, who reliably differ from non-smokers in traits affecting cognitive control like impulsivity and sensation seeking (Baker et al., 2004; Ryan et al., 2013), and who behave highly risky in a variety of real-life situations (Hersch & Viscusi, 1998), show lower rDLPFC activity in cognitive control tasks than non-smoking controls (Nestor et al., 2011).

However, the interpretation of these findings in terms of cognitive control is problematic because the tasks commonly used to study risky decision-making behavior did not allow for a clear separation between affect-charged and deliberative processes (Figner et al., 2009). Hence, some authors have interpreted rDLPFC activity during risky decision making in terms of deliberative thinking (Rao et al., 2008; Mohr et al., 2010), although evidence for the involvement of the DLPFC in deliberative processing is most prominent for the left (l)DLPFC in healthy (see Vallar & Bolognini, 2011; for review) as well as clinical populations (see Demirtas-Tatlidede et al., 2013, for review).

We assessed hemispheric transcranial direct current stimulation (tDCS) effects on risky decision making by means of placing a small-sized anodal electrode over the rDLPFC with a big-sized cathode over the IDLPFC (anodal right/cathodal left) and vice versa (i.e. small anode left/big cathode right). Different sizes of electrodes were used for two reasons: first to improve focality of anodal tDCS; and second to maximize the facilitating neuronal effect of the anode...
and to minimize the inhibitory effect of the cathode (see Materials and methods: tDCS). The experimental task we used [Columbia Card Task (CCT); Figner et al., 2009] was specifically designed to assess risky decision making under differential involvement of deliberative vs. affective processes. Furthermore, by including a group of smokers and non-smokers, we aimed to assess if individual differences in risk-taking propensity can be attributed to lateral PFC functions.

**Materials and methods**

**Participants**

Forty healthy university students participated in the study. Students received course credits for participation, independent of their performance in the CCT. Four participants had to be excluded for incomplete behavioral data. The remaining sample consisted of 18 smokers (age: mean ± SD, 22.4 ± 2.5 years; 10 females) and 18 non-smokers (21.0 ± 1.5 years; 15 females). Smokers had been smoking at least 10 cigarettes per day for at least 1 year, and had a non-smokers (age: mean ± SD, 21.5 ± 1.4 in the Fagerström Test for Nicotine Dependence [Heatherton et al., 1991]). Participants were all right-handed, as assessed by the Edinburgh Handedness Inventory (Oldfield, 1971), with normal or corrected-to-normal vision, and had been screened for the absence of present or past neurological or psychiatric conditions and use of psychoactive medication. All were naive to the goals of the experiment, and gave informed written consent. The study was conducted in conformity to the Declaration of Helsinki and approved by the ethics committee of the University of Vienna.

**Experimental design**

In a within-subjects design, each participant joined three tDCS sessions with different stimulation conditions [anodal electrode placed over the IDLPFC with the cathode placed over the rDLPFC (anodal left/cathodal right), anodal electrode placed over the rDLPFC with the cathode placed over the IDLPFC (anodal right/cathodal left), and sham stimulation], with at least 1 week between sessions. The sequence of stimulation conditions was counterbalanced across participants. For sham stimulation, electrode positions of both verum stimulations (anodal left/cathodal right, anodal right/cathodal left) were balanced across participants. The sequence of the tasks, i.e. the Hot and Cold version of the CCT (see below), was counterbalanced across participants, but task order was kept constant within participants for the three sessions to avoid confounding task order effects with stimulation conditions.

After electrode application, participants were seated in a comfortable chair in a sound-attenuated, dimmed room equipped with an intercom to the experimenter. Before starting the stimulation, participants were given a training session to familiarize them with the CCT, which was presented on a 19-Zoll-CRT-Monitor placed at a 60-cm viewing distance. Participants were instructed to sit quietly with their eyes open for the first 5 min of stimulation, after which task presentation started. Stimulation of the verum sessions was terminated after 15 min. Processing of the tasks lasted a few (3–5) minutes longer, depending on the individual reaction times. Note that verum post-stimulation effects have been documented to last at least for 1 h (Nitsche & Paulus, 2001). After electrode removal, participants had to answer a questionnaire about the adverse effects of brain stimulation (based on Brunoni et al., 2011).

**CCT**

In the CCT, participants are instructed to maximize their game scores during each game round by choosing how many cards they would like to draw out of a total of 32 hidden gain or loss cards. An optimal strategy to maximize the total score needs to take into account three factors, which are orthogonally varied by trial: (a) probability of a loss (pL = 1 or 3 loss cards); (b) gain amount [GA = 10 (low) or 30 (high) points per gain card]; and (c) loss amount (LA = 250 or 750 points). In the 24 rounds of the ‘Hot’ task version of the game, participants make stepwise incremental decisions by turning only one card at a time with immediate feedback provided after each choice. At any point in each round, participants can choose to stop their card selection (thus obtaining the round’s payoff), or continue to choose cards until a losing card is selected (which leads to a subtraction of the LA in that round, and ends the round). This dynamic nature in which risk increases over time within a trial is similar to other risk-taking tasks like the Balloon Analogue Risk Task (Lejuez et al., 2002), which has also been used in previous tDCS studies (e.g. Fecteau et al., 2007b; Boggio et al., 2010a). The position of loss cards was randomized for each round and not fixed (as in Figner et al., 2009), in order to avoid the impression of rigged feedback (for details, see Figner et al., 2009). In the ‘Cold’ task version of the game, decisions are not made step-wise and there is no immediate feedback. Instead, participants are asked to indicate only the number of cards (from 0 to 32) they would like to turn over on a given trial. Players receive feedback on their performance only at the very end of the whole CCT session, by means of a summary score after the last of the 24 rounds.

According to Figner et al. (2009), the number of cards chosen, independent of the game factors, represents an index of risk-taking, while the number of cards chosen as a function of the game factors represents an index of information use. It is crucial to note that the two versions of the CCT elicit different decision-making processes. The Hot CCT elicits higher emotional arousal, as indexed by electrodermal activity, is positively correlated with the motivational-affective construct need-for-arousal, and has been shown to elicit strategies predominantly based on affect-charged decision-making behavior. The Cold CCT, in contrast, elicits strategies predominantly based on mathematical calculations and reasoning, and has been shown to be independent from impulsive personality characteristics (Figner et al., 2009). Hence, risk-taking in the Hot CCT is more strongly influenced by affective processes, while deliberative decision-making processes prevail in the Cold CCT.

**tDCS**

Anodal tDCS was delivered over three sintered Ag/AgCl electrodes (sized 5.3 cm² in total), which were connected by an electrode splitter cable (1 to 3) to the anodal output of a battery-driven, constant-current stimulator (DC-STIMULATOR PLUS, neuroConn GmbH, Erlangen, Germany). Small electrodes were used for anodal stimulation to improve the locality of tDCS (Marshall et al., 2004; Nitsche et al., 2007; Datta et al., 2009; Faria et al., 2009; Miranda et al., 2009; Minhas et al., 2010). Positions F1, F3 and AF1 according to the international 10–20 electrode system (Jasper, 1958) were used for left hemisphere anodal stimulation (‘anodal left/cathodal right’ hitherto). For right hemisphere anodal stimulation (‘anodal right/cathodal left’), electrodes were positioned at F2, F4 and AF2. Electrodes were positioned and kept in place by using an elastic and individually fitted electroencephalogram (EEG)-cap (EASYCAP Ges.m.b.H., Herrsching, Germany). The 7 × 5 cm² cathodal reference
electrode was centered contralateral at positions F3 and F4, respectively, with the short side running in parallel to the imaginary Cz-Fz connecting line. Stimulation electrodes were filled with degassed electrode gel (Electro-Cap International, Eaton, USA), and the skin under the electrodes had been cleaned with alcohol and slightly scratched to decrease skin resistance (Bauer et al., 1989). This method assured electrode impedance values of \( \leq 3 \, \text{k} \Omega \), as individually measured by an impedance meter (Ing., Zickler Ges.m.b.H., Pfaffstätten, Austria). At the side of the surface sponge electrode the skin was only cleaned with alcohol, but not scratched, as this might have created unwanted focal cathodal stimulation effects.

A direct current of 0.45 mA intensity, resulting in an anodal current density of 0.085 mA/cm\(^2\), was induced for 15 min in the verum sessions, and for 30 s with 30 s fade-in and 30 s fade-out in the sham session. Modeling studies showed that 0.45 mA delivered over an electrode size of about 5 cm\(^2\) induces a comparable current intensity at the surface of the cortex to 1 mA over a 35 cm\(^2\) electrode (Miranda et al., 2009). At the cathode a direct current density of 0.013 mA/cm\(^2\) was induced. Because a minimum current density of 0.017 mA/cm\(^2\) was previously shown to be necessary to modify motor cortex excitability by tDCS (Nitsche & Paulus, 2000), current density at the reference electrode might be considered as functionally irrelevant.

Assessment of personality characteristics

Participants had to answer questionnaires assessing cognitive control-related personality characteristics [Barratt Impulsiveness Scale (BIS11), Patton et al., 1995; Substance Use Risk Profile Scale (SURPS), Woicik et al., 2009; BIS/BAS scale, Carver & White, 1994] and one additional question concerning risk-aversion: “It frightens me when I have to make decisions which involve risk” (four-point scale: strongly disagree; disagree; agree; strongly agree).

Data analysis

The main outcome measures were the number of cards chosen. To account for differences in the procedures and the interpretation of the game parameters, the Hot and Cold versions of the CCT were analysed using separate statistical analyses. Linear mixed models with restricted maximum likelihood estimation were used to control for heteroscedasticity and to include time-dependent covariates, which was necessary because of the within-subject design (Gueorguieva & Krystal, 2004; McCulloch & Searle, 2005; Heck et al., 2011). For the two versions of the CCT we evaluated the within-subjects fixed factors ‘stimulation condition’ (sham, anodal left, anodal right), ‘GA’ (low, high), ‘LA’ (low, high) and ‘pL’ (low, high); the between-subjects fixed factor ‘smoking group’ [smokers (S), non-smokers (NS)] and the random factor ‘subjects’ in a full-factorial model. For the Hot version the number of cards chosen in the Cold CCT and the number of negative feedbacks were introduced as model. For the Hot version the number of cards chosen in the risky gamble) in the Cold CCT, averaged across smokers and non-smokers. Anodal left/cathodal right stimulation over the DLPFC led to a decrease in risk-taking, in comparison to sham stimulation; whereas anodal right/cathodal left stimulation had no effect. Left: anodal left/cathodal right; right: anodal right/cathodal left.

Results

Adverse effects

The frequencies of reported adverse effects did neither differ between the three stimulation conditions nor between smokers and non-smokers, except that more non-smokers reported itching sensations during anodal left stimulation (61% vs. 22%). The three most frequently reported adverse effects were sleepiness (56%), tingling (45%) and itching (32%).

Questionnaire data

As for the questionnaire data, smokers scored higher in the SURPS subscales ‘Impulsivity’ (S = 10.3 ± 1.5; NS = 8.8 ± 1.9; S = 2.525, P = 0.016) and ‘Sensation Seeking’ (S = 17.8 ± 2.6; NS = 14.7 ± 2.1; S = 3.947, P < 0.001), and in the BIS11 total score (S = 67.3 ± 7.2; NS = 57.9 ± 8.6; S = 3.592, P = 0.001). Non-smokers scored higher in the SURPS ‘Anxiety Sensitivity’ subscale (S = 10.8 ± 2.9; NS = 12.8 ± 3.0; S = –2.047, P = 0.048), the inhibition scale (BIS) of the BIS/BAS scale (S = 19.5 ± 4.3; NS = 22.7 ± 3.9; S = –2.319, P = 0.027) and the risk-aversion scale (S = 2.2 ± 0.5; NS = 2.9 ± 0.7; S = –3.370, P = 0.002).

Cold CCT

Analysis of the Cold CCT revealed a significant main effect for stimulation condition (F \(_{2,351} = 4.330, P = 0.014\). Bonferroni post hoc tests showed that anodal left/cathodal right (P = 0.014) but not anodal right/cathodal left (P = 1.000) stimulation resulted in decreased risk-taking compared with sham stimulation (Fig. 1).
Further significant main effects revealed that the number of chosen cards was higher for trials with high GA ($F_{1,556} = 95.339$, $P < 0.001$), low LA ($F_{1,556} = 381.664$, $P < 0.001$) and lower pL ($F_{1,556} = 506.338$, $P < 0.001$).

In addition, there were significant interactions for GA $\times$ pL ($F_{1,556} = 9.976$, $P = 0.002$) and LA $\times$ pL ($F_{1,556} = 17.903$, $P < 0.001$). However, none of the interactions with stimulation condition was significant (all $P$-values $> 0.1$). This pattern of findings for the gamble factors reveals that information about risk conditions was appropriately used by participants, but that information use was not modulated by tDCS stimulation.

Further significant interactions were found for smoking group $\times$ GA ($F_{1,556} = 5.090$, $P = 0.024$) and smoking group $\times$ pL ($F_{1,556} = 9.333$, $P = 0.002$). Bonferroni post hoc tests showed that smokers took higher risks than non-smokers under conditions of high GA ($P = 0.037$), as well as under conditions of low pL ($P = 0.027$). All other main effects and interactions were non-significant (all $P$-values $> 0.08$), including the interaction group $\times$ stimulation ($P = 0.318$).

Hot CCT

The analysis of the Hot condition revealed neither a significant main effect for smoking group nor for stimulation condition (all $P$-values $> 0.195$), but a significant interaction of stimulation condition $\times$ smoking group ($F_{2,361} = 6.324$, $P = 0.002$). Bonferroni post hoc tests revealed that smokers showed a decrease in risk-taking during anodal right/cathodal left compared with sham stimulation ($P = 0.046$), whereas non-smokers showed the opposite pattern, i.e., an increase in risk-taking under anodal right/cathodal left compared with sham stimulation ($P = 0.031$). Furthermore, compared with non-smokers, smokers took significantly higher risk during the sham condition ($P = 0.010$), but not during anodal left/cathodal right or anodal right/cathodal left stimulation (all $P$-values $> 0.1$; Fig. 2).

Note that when conducting an analysis without covariates the results were essentially identical (stimulation condition $\times$ smoking group: $F_{2, 352} = 7.245$, $P = 0.001$).

In the Hot CCT, significances of main effects and interactions of the gambling factors, i.e., GA ($F_{1,556} = 46.229$, $P < 0.001$), LA ($F_{1,556} = 54.783$, $P < 0.001$), pL ($F_{1,683} = 296.130$, $P < 0.001$) and GA $\times$ pL ($F_{1,515} = 17.402$, $P < 0.001$), were similar to the Cold version except for LA $\times$ pL, which was very close to the chosen significance threshold though ($F_{1,519} = 3.162$, $P = 0.076$).

Furthermore, significant interactions were found for smoking group $\times$ LA ($F_{1,510} = 5.336$, $P = 0.021$), smoking group $\times$ pL ($F_{1,515} = 5.811$, $P = 0.016$) and smoking group $\times$ GA $\times$ LA ($F_{1,510} = 4.005$, $P = 0.046$). Bonferroni post hoc tests revealed that in the Hot CCT smokers showed particularly higher risk-taking than non-smokers in conditions that combine high GA with low LA ($P = 0.015$), and on a trend level in conditions with low pL ($P = 0.058$). In analogy to the Cold CCT these patterns were not affected by the type of stimulation ($P$-values $> 0.1$).

Discussion

We used two different versions of a risky decision-making game, and investigated whether anodal left/cathodal right or anodal right/ cathodal left tDCS over the DLPFC influences the risky choices made in this game in two different groups (S vs. NS). To improve focality and emphasize the facilitating effect of anodal stimulation, a small-sized anode and a big-sized cathode were used. Our results demonstrate that tDCS over the DLPFC affects risky decision making, and that these effects are modulated by the stimulated hemisphere, the type of task and the group. Briefly, anodal left/cathodal right stimulation decreased risk-taking in the ‘cold’ cognition version of the task, in both groups, while in the ‘hot’ version, anodal right/cathodal left stimulation decreased risk-taking in smokers and increased it in non-smokers.

In terms of their general behavior, participants acted in line with theoretical predictions and previous observations using similar task setups (Figner et al., 2009). Most importantly, information use was as expected in both the Cold and the Hot CCT, because higher GA, lower LA and a lower pL all resulted in a higher number of cards chosen (i.e., risks taken). However, the difference in cards chosen between the Hot and Cold CCT was reversed and smaller in our version except for LA $\times$ pL, which provides feedback at the trial by trial level, rather than the further support this interpretation. They used the ‘Warm CCT’, which provides feedback at the trial by trial level, rather than the card by card level, to avoid participants detecting the rigged nature of feedback. This manipulation on the feedback strategy of the Hot, respectively, Warm CCT resulted, in agreement with our observations, in more cards turned over on average in the Cold CCT than in the Warm CCT, but with the Warm CCT still arousing stronger emotions (Huang et al., 2013). When comparing information use of smokers and non-smokers, similar patterns could be observed for the two versions of the CCT. For instance, smokers took higher risks than non-smokers when pL was low (Hot and Cold CCT), when there was much to win (Cold CCT), and in trials that
combined high wins with low LA (Hot CCT). However, these decision patterns were not affected by the type of stimulation.

The results of the Cold CCT, in which more cautious decisions were obtained after anodal left/cathodal right but not anodal right/cathodal left stimulation in both groups, are in agreement with our hypothesis. The Cold CCT has been shown to elicit strategies predominantly based on mathematical calculations, and does not correlate with the need-for-arousal construct (Figner et al., 2009). Thus, decision making in the Cold CCT is said to be independent from personality characteristics, such as impulsivity or sensation seeking (Figner et al., 2009). This assumption fits well with the lack of baseline differences in risk-taking between smokers and non-smokers in the Cold CCT. We attribute the decrease in risk-taking after anodal left/cathodal right stimulation over the DLPFC in both groups to a modification of deliberative reasoning and stimulus processing. This interpretation is supported by results showing that particularly stimulation with the anode placed over the IDLPFC results in the modification of executive processes that play a major role in deliberative processing, such as working memory (Keesser et al., 2011b), probabilistic reasoning (Hecht et al., 2010) and planning (Dockery et al., 2009). A recent study by Xue et al. (2012) further supports this interpretation. Based on functional magnetic resonance imaging (fMRI) data showing the left DLPFC being strongly activated in strategic decision making, subsequently applying anodal tDCS over this region resulted in modification of the decision-making strategy.

Our hypothesis concerning the effect of tDCS on affect-charged risky decisions (as assessed by the Hot CCT) could partly be confirmed. As expected, we did not find significant modulation of risk-taking by anodal left/cathodal right stimulation over the DLPFC in either group. More importantly, anodal right/cathodal left stimulation decreased risk-taking, but only seen in smokers, whereas non-smokers showed increased risk-taking. When interpreting this opposite effect on risk-taking for smokers and non-smokers, differences in baseline risk behavior need to be taken into account. Comparing the baseline level of risk-taking, i.e. risk-taking during sham stimulation, smokers showed significantly higher risk-taking than non-smokers in the Hot CCT. This is in agreement with previous findings (e.g. Hersch & Viscusi, 1998; Lejuez et al., 2003; Hakes & Viscusi, 2007; Anderson & Mellor, 2008). Furthermore, and as predicted, these differences in risk-taking were accompanied by individual differences in personality characteristics (e.g. Fields et al., 2009; Ryan et al., 2013): while smokers scored higher in impulsivity (SURPS, BIS11) and sensation seeking (SURPS), non-smokers showed higher behavioral inhibition (BIS scale), anxiety sensitivity (SURPS) and risk-aversion.

Based on this pattern of findings, the opposing tDCS effects in the two groups might be explained by the engagement of the same inhibitory control mechanism associated with rDLPFC (Knoch et al., 2006). In smokers, with their higher impulsivity and sensation seeking, increased cognitive control of affective impulses leads to a reduction of risky decisions. In the risk-averse and more loss-sensitive non-smokers, on the other hand, cognitive control might act upon and inhibit the influence of bottom-up aversive impulses signaling to be careful in risky choices – hence resulting in less conservative and therefore more risky decisions. Two lines of evidence support this interpretation: first, it has been shown that low sensation seekers, as the non-smokers in our study, display enhanced anxious anticipation of negative consequences. For example, indicators of anticipatory aversive affect, such as fear-potentiated startle responses to unpredictable stimuli, are increased in low sensation seekers (Lissek et al., 2005). This suggests a stronger bottom-up engagement of aversive physiological and affective responses in unpredictable situations, such as risky decisions. Second, it has been shown that stimulation by means of anodal right/cathodal left tDCS over the DLPFC can boost response confidence during risky decisions in healthy risk-averse participants (Minati et al., 2012a), and this has been attributed to strengthened cognitive control (Camchong et al., 2007).

Concerning the often reported risk-seeking propensity of smokers, our results support the longstanding idea in psychology that resisting temptations reflects competition between impulses and self-control (Hofmann et al., 2009). Strengthening self-control by means of increasing rDLPFC activation helps smokers to stifle risk-seeking impulsivity. However, our data do not allow concluding that increased risk-taking of smokers is due to maladaptive cognitive control (Feil et al., 2010; Goldstein & Volkow, 2011). Our results rather show that different personality characteristics, i.e. smokers being risk-seekers and non-smokers scoring not only lower in sensation seeking and impulsivity but also higher in risk-aversion and anxiety sensitivity, are responsible for the observed differences in risk-taking between groups.

It might be argued that general differences in the cognitive processes and task demands engaged by the Hot and Cold CCT, termed ‘learning demands’ by Figner et al. (2009), might be an alternative explanation for the reported results. For instance, the Hot CCT requires participants to keep track of the increasing probability of losing with each card they have turned over. This might involve higher demands on working memory, which has also been associated with DLPFC function. However, what speaks against this alternative explanation is the fact that smokers and non-smokers showed effects in opposite directions in the Hot CCT – contradicting a general effect attributable to modulation of working memory function. Furthermore, neither Figner et al. (2009) nor Huang et al. (2013) found any evidence for differential “learning demand” effects for the Cold and Hot CCT versions in their studies.

As the Cold CCT was designed to trigger mainly deliberative decision making (Figner et al., 2009), but not exclusively, it could also be argued that the Cold CCT is not completely free of affective processes. This could make it difficult to separate deliberative from affective processing in the two versions of the CCT. However, those versions of the CCT that have been designed to engage affective processes (i.e. the Hot CCT and the Warm CCT) indeed seem to elicit stronger emotions during decision making than the Cold CCT, as shown in previous behavioral studies (Figner et al., 2009; Huang et al., 2013). Furthermore, the study by Figner et al. (2009) demonstrated that the Cold CCT elicits strategies predominantly based on mathematical calculations and reasoning, while strategies to solve the Hot CCT are predominantly based on affect-charged decision-making behavior, as shown by self-reported decision strategies. While Huang et al. (2013) could not replicate these differences in strategies when comparing the Warm CCT with the Cold CCT, this might have been due to limitations of the self-report measures used, according to the authors. Thus, although minor affective processing might have been induced during playing the Cold CCT, results of the Cold CCT of our study are more plausibly explained in terms of involvement and modification of deliberative processes.

It should further be noted that ‘cognitive inhibitory control’ or ‘cognitive control’ is necessary for a variety of impulsive behaviors (for an overview, see Ohmura et al., 2012), like impulsive action (e.g. Go/No Go task or stop-signal-reaction-time task; e.g. Logan et al., 1997; Steinbeis et al., 2012); impulsive choice (e.g. delay discounting; e.g. Cho et al., 2012); risky behavior (for review, see Boyer, 2006); or substance craving (e.g. George & Koob, 2011; Hayashi et al., 2013). Our study refers to cognitive control in risky behavior.
behavior, i.e. limiting the influence of affect in risky decision making. Cognitive control in other impulsive behaviors might be based on partly overlapping (for review, see Cohen & Lieberman, 2010), but probably not identical, brain mechanisms. Comparing, for example, the effects of high-frequency repetitive transcranial magnetic stimulation (rTMS) over the DLPFC (with rDLPFC not studied) on delay discounting and risky decision making [Risky Choices Gambling Task (RCGT)] in the same sample (smokers and non-smokers), significant modification of delay discounting compared with sham stimulation was observed, but there was neither a difference between the active and sham rTMS condition for risky decision making nor for cigarette consumption (Sheller et al., 2013). Using the same risk task, i.e. the RCGT, Knoch et al. (2006) found that inhibiting activity by rTMS over the right, but not over the left, DLPFC modulates risky decision making, which is in agreement with our observations in particular because the RCGT measures mainly affect-charged risky decision making with little strategic planning. Together, these findings speak against a domain general cognitive inhibitory control mechanism within the DLPFC and for a prominent role of the rDLPFC for cognitive control of affective processes in risky decision making.

It has also been proposed that non-invasive brain-stimulation treatment effects of addiction are linked to shifts in decision making related to the role of the DLPFC in impulsivity control (e.g. Boggio et al., 2010b; for review, see Fecteau et al., 2010). However, as our study did not assess craving and the effects of the specific electrode setting used in our study have never been explored for the potential to modify craving, testing this hypothesis is not within the scope of this study.

In general, the spatial resolution of tDCS is known to be limited. To improve spatial specificity and emphasize the facilitating effect of the anodal stimulation, we used small EEG electrodes focused over the DLPFC, and a large sponge electrode was placed contralateral with the intention to make the cathode functionally ineffective (Marshall et al., 2004; Nitsche et al., 2007; Datta et al., 2008; Minhas et al., 2010). Nevertheless, the exact distribution of the electric field generated by tDCS is not known (Datta et al., 2009; Dmochowski et al., 2011; Faria et al., 2011), and cathodal functional ineffectiveness of current densities below 0.017 mA/cm² as used in this study (0.013 mA/cm²) has only been shown for the motor cortex (Nitsche & Paulus, 2000) but not for other regions. Further studies, in particular ones providing information on the precise neural effects, such as combinations of tDCS with fMRI, are therefore necessary to clarify the influence of such electrode settings on DLPFC activity and whether other areas were also stimulated and therefore might contribute to the observed effects (Keesser et al., 2011a). The specific stimulation protocol used, particularly the combination of small-sized EEG electrodes with a big-sized sponge electrode, and the consideration of personality characteristics in our study might also explain some disparity to results of other studies dealing with risky decision making and non-invasive brain stimulation of the DLPFC (Fecteau et al., 2007a,b).

We show that anodal right/cathodal left tDCS over the DLPFC predominantly modulates regulation of affective impulses, and the opposite electrode setting, i.e. anodal left/cathodal right stimulation, mainly influences deliberative processing of risky decision-making behavior. Upregulating the activity of the rDLPFC seems to increase cognitive control of affective impulses. However, the direction of effects on risk-taking when strengthening cognitive control depends on the valence of affective impulses: improved controllability of risk-seeking temptations leads to more conservative decisions vs. inhibition of risk-averse apprehensiveness results in riskier choices.

These findings are relevant for mechanistic models of decision making, and suggest that individual differences, the type of decisions and hemispheric variability need to be taken into account in such models. Our results also provide further insights into the development of interventions using non-invasive brain stimulation to treat psychiatric disorders associated with decision-making problems, such as addiction or depression.

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Abbreviations

BIS, Barratt Impulsiveness Scale; CCT, Columbia Card Task; DLPFC, dorsolateral prefrontal cortex; EEG, electroencephalogram; fMRI, functional magnetic resonance imaging; GA, gain amount; LA, loss amount; IDLPFC, left dorsolateral prefrontal cortex; NS, non-smoker; PFC, prefrontal cortex; RCGT, Risky Choices Gambling Task; rDLPFC, right dorsolateral prefrontal cortex; rTMS, repetitive transcranial magnetic stimulation; S, smoker; SURPS, Subtance Use Risk Profile Scale; tDCS, transcranial direct current stimulation.

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