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Transcranial stimulation over the dorsolateral prefrontal cortex increases the impact of past expenses on decision-making

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Abstract

Goal-directed choices should be guided by the expected value of the available options. However, people are often influenced by past costs in their decisions, thus succumbing to a bias known as the 'sunk-cost effect'. Recent functional magnetic resonance imaging (fMRI) data show that the sunk-cost effect is associated with increased activity in dorsolateral prefrontal cortex (dlPFC) and altered crosstalk of the dlPFC with other prefrontal areas. Are these correlated neural processes causally involved in the sunk-cost effect? Here, we employed transcranial direct current stimulation (tDCS) to examine the role of the dlPFC for biasing choices in line with the cost of past expenses. Specifically, we applied different types of tDCS over the right dlPFC while participants performed an investment task designed to assess the impact of past investments on current choices. Our results show a pronounced sunk-cost effect that was significantly increased by anodal tDCS but left unaltered by cathodal or sham stimulation. Importantly, choices were not affected by stimulation when no prior investments had been made, underlining the specificity of the obtained effect. Our findings suggest a critical role of the dlPFC in the sunk-cost effect and thus elucidate neural mechanisms by which past investments may influence current decision-making.

Keywords: dlPFC, sunk-cost effect, value-based decision-making, brain stimulation, tDCS

According to traditional economic theory, humans should base their decisions on the expected future value of the choice-relevant objects, investments or experiences (Edwards 1954; Frank and Bernanke 2006; Cabantous and Gond 2011). Choices in everyday life, however, are often not that rational and smart (Tversky and Kahneman 1974; Samuelson and Zeckhauser 1988; Kahneman et al. 1991 Shafir et al. 1993). In particular, when people have invested time, money or effort into an option, they are often reluctant to abandon it even though its expected value is not favorable anymore. This tendency to consider past costs that cannot be recovered in current decision-making is referred to as the 'sunk-cost effect' (Arkes and Blumer 1985). The sunk-cost effect has been demonstrated in numerous studies (Garland 1990; Arkes and Hutzel 2000; van Putten et al. 2010) and it is among the most consequential biases in human decision making: it can explain why people remain in a failing relationship (Strube 1988) or why they are unable to leave a dissatisfying job (Arkes and Blumer 1985), it may push up prices in auctions (Murnighan 2002), drive wars or keep failing policies alive (Staw 1976).

The past decade has seen significant progress in our understanding of the neurobiological underpinnings of human decision making (Gold and Shadlen 2007; Kable and Glimcher 2007; Rangel et al. 2008; Hare et al. 2009; Rushworth et al. 2011; Delgado and Dickerson 2012; Ruff and Fehr 2014). A large network of interconnected areas has been implicated in decision-making, including the amygdala, the anterior cingulate cortex, the parietal cortex and the ventral striatum (Bechara et al. 1999; Sanfey et al. 2003; De Martino et al. 2006; Kennerley et al. 2006; Leotti and Delgado 2014). For the representation of the expected value of an option, which lies at the heart of rational decision-making, the orbitofrontal cortex (OFC) and the ventromedial prefrontal cortex (vmPFC) have been identified as crucial neural components (Kable and Glimcher 2007; Grabenhorst and Rolls 2011; Jocham et al. 2012). A recent study provided first insights into the neural signature of the sunk-cost effect (Haller and Schwabe 2014). This study showed that prior investments reduce the activity of the vmPFC during subsequent decisions and that this reduction in vmPFC activity correlates with the magnitude of the sunk-cost effect. Moreover, in line with previous behavioral studies (Arkes and Ayton 1999), the sunk-cost tendency was associated with the norm not to be wasteful. Social norms are thought to be represented in the dorsolateral prefrontal cortex (dlPFC; Sanfey 2003; Baumgartner et al. 2011), and several aspects of the data were consistent with this: First, the norm not to waste resources correlated with the activity of the right dlPFC, and second, the right dlPFC showed increased connectivity with the vmPFC when participants had already made an investment into a certain course of action, compared to when not. Thus, these data suggest a model for the neural origins of the sunk-cost effect in which the dlPFC, representing the norm not to waste resources, is activated once an investment has been made and overrides the vmPFC, thus hampering rational choices based on expected values.

One obvious weakness of the model proposed above is that it is based solely on functional magnetic resonance imaging (fMRI) data, which are correlational by nature and therefore not informative about causal relationships between brain activity and behavior. To formally test for such a causal relationship, we employed transcranial direct current stimulation (tDCS), a method for non-invasive stimulation of the human brain by means of weak electric currents (Nitsche and Paulus 2000) that has already successfully been used for demonstrating the involvement of a brain area in decision-making processes (Fregni et al. 2005; Ruff et al. 2013; Davis et al. 2014). In the present study, we examined how tDCS applied over the dlPFC affects the biasing influence of past, irrecoverable costs on current decision-making. To this end, participants performed an investment task that was recently introduced to examine the sunk-cost effect (Haller and Schwabe 2014). While participants performed this task, we applied anodal, cathodal, or sham stimulation over the right dlPFC, as our previous fMRI data showed that in particular the activity of the right dlPFC was linked to the sunk-cost effect (Haller and Schwabe 2014). Anodal and cathodal tDCS are known to increase or decrease the resting potential and therefore neural excitability in the targeted regions, respectively (Nitsche and Paulus 2000), whereas sham tDCS mimics the peripheral effects (i.e., tactile sensations) associated with tDCS while not affecting neural processing (Nitsche et al. 2008). We therefore expected that anodal stimulation over the dlPFC would increase dlPFC activity (and possibly other connected areas), thereby enhancing the impact of previous investments on decision-making compared to sham stimulation, whereas cathodal stimulation might even have the opposite effect of reducing the sunk-cost effect.

Materials and Methods

Participants and Experimental Design

Sixty healthy men and women between 18 and 32 years of age participated in this experiment (mean age ± SEM: 24.9 ± 3.6 years; 30 women). Exclusion criteria for participation were checked in a standardized interview prior to testing and comprised current illness, medication intake, a life-time history of any neurological disorders as well as any contraindications for tDCS. Participants gave written informed consent before the start of testing and received a compensation of 12 Euros plus what they won in the investment task at the end of the experiment. The study was approved by the ethics committee of the German Psychological Association (DGPs).

In a double-blind, sham-controlled, between-subject design, participants were randomly assigned to one of three stimulation conditions (10 men and 10 women per group): anodal, cathodal, or sham stimulation of the dlPFC. The stimulation lasted for as long as the individual participant worked on the investment task but not longer than 30 minutes.

Questionnaires

In order to control for personality traits and behavioral tendencies that are relevant within the context of the sunk-cost effect and decision-making in general, participants filled out several questionnaires at the beginning of the experiment. In particular, participants completed the

German versions of the Behavioral Inhibition/Behavioral Activation System scales (BIS/BAS scales, Carver and White 1994), the NEO-Five Factor Inventory (NEO-FFI, McCrae and Costa 2004), the Barratt-Impulsiveness-Scale (BIS-15, Spinella 2007), and a short questionnaire that assessed the individual sunk-cost tendency and the desire not to appear wasteful (Haller and Schwabe 2014). The latter consists of 8 items that should be answered on a scale from 1 ("I do not agree") to 11 ("I completely agree"). Example items were "I finish a started project, no matter the cost" or "People who know me think I am wasteful". A sum score for both the sunk-cost tendency and the desire not to appear wasteful was calculated by summing up the scores for the four items of each scale.

Investment Task

The sunk-cost effect was examined with a modified version of a recently developed investment task (Haller and Schwabe 2014) that was adapted to the time constraints associated with the safe use of tDCS. In total, participants performed 252 trials of this investment task (average duration: 28 minutes). On each of these trials, participants were presented with a project characterized by its costs and probability of success (Figure 1). The costs were either low (0.20 or 0.25 cents) or high (0.60 or 0.65 cents). The probability of success was low (40%), medium (50%), or high (60%) and corresponded to the actual probability of success implemented in the program. These probabilities were chosen based on a pilot study showing that probabilities that were higher than 60% or lower than 40% result in ceiling and floor effects, respectively (Haller and Schwabe 2014). Participants were instructed to decide whether or not they wanted to invest the indicated amount of money in the project, by pressing either the right or left arrow key on a keyboard. If the participants did not respond within 5 s or if they decided not to invest, the trial was aborted. If the participants decided to invest, they either received immediate feedback about the success of the project (as determined by the computer program based on the given probability), or they were informed that further investments would be necessary. If a second investment decision was required, participants were presented with the additional costs and the updated probability of success; again the costs could be low or high and the probability of success could be low, medium, or high. Participants had again 5 s to decide whether they wanted to invest the additional money in the project or whether they wanted to abort it. Thus, the only difference between the first and second investment scenario was whether or not participants had already invested in the project. If participants decided to continue to invest, they were given immediate feedback about the success of the project, i.e., there was a maximum of one follow-up investment.

For the initial investment trials, each of the six combinations of costs (low vs. high) and probability of success (low vs. medium vs. high) was presented 42 times (252 trial in total). In one third of the trials, no second investment decision ensued ("no prior investment trials"). In the rest of the trials, participants were asked to decide whether they wanted to make a second investment required for the possible success of the project they had already invested in. This was done to ensure that there were sufficient trials to investigate the influence of past investments on current decisions. Trials in which a follow-up decision was required were subdivided into those in which the initial investment was low and those in which the initial investment was high ("low prior investment trials" and "high prior investment trials", respectively). Apart from the size of the previous investment (none, low, high), the three types of trials were identical, as all possible costs × probability combinations were presented equally often in these trials. The different trial types were presented in random order. Between trials, a fixation cross was presented for 1 to 3 s (random jitter: 2 s).

Critically, participants were told that they would gain 2 Euros for every project that was completed successfully, but that they would have to pay all investments made regardless of the success of a project. It was made clear that, in "prior investment trials", the probability of the first and second decisions were independent and that the initial investments were lost, irrespective of the follow-up decision. Participants were further instructed that the computer would randomly choose 10 trials at the end of the experiment and calculate their associated gains or losses. These would then be added to or subtracted from the participants' compensation. In order to make sure that participants fully understood the decision-making task, we asked them to repeat the essential features of the task after they had received the task instructions. Possible misconceptions were clarified. In particular, we emphasized that, in prior investment trials, the probabilities in the initial and follow-up decision scenarios are independent and that any initial investment is lost, irrespective of the follow-up decision.

Transcranial Direct Current Stimulation (tDCS)

Brain stimulation was applied in a double-blind, sham-controlled manner using a Neuroconn stimulator (Neuroconn, Germany). In line with previous tDCS studies that focused on the dlPFC (Harty et al. 2014; Zwissler et al. 2014; Axelrod et al. 2015; Pope 2015), we used an EEG cap and the standard 10-20 system to determine electrode positions individually for each participant. The smaller electrode (5×5 cm) was positioned over the right dlPFC (position F4). The larger electrode (10×10 cm), which served as a reference (Nitsche et al. 2007), was fixed centrally on the head (position CZ). Different electrode sizes were chosen so that a higher, functionally more effective current density was applied over the dlPFC (the area of interest) than over the central regions underlying the large electrode. Both electrodes were covered in sponges soaked with a sodium chloride solution to improve conductivity and to reduce skin irritation. For active stimulation, we applied a current of 1.075 µA, leading to a current density of 0.043 mA/cm² for the electrode over the dlPFC and 0.011 mA/cm² for the reference electrode, making it much less likely for the larger electrode to induce functional effects on the underlying brain tissue. The electrode setup was identical in all conditions. In the anodal condition, the electrode over the dlPFC served as the anode whereas the reference electrode served as the cathode. In the cathodal condition, the polarity of the electrodes was reversed. Active brain stimulation lasted 30 minutes at most and was stopped once the participant had finished the investment task. In all conditions, the current was applied with an 8-s-fade-in and a 5-s-fade-out-window at the beginning and the end of the stimulation. In the sham condition, no current was delivered after the initial fade-in-period, to prevent participants from being able to tell to which condition they had been assigned to. Blinding of the investigator and the participant was accomplished by using pre-programmed codes of the Neuroconn-stimulator. Since the stimulation condition was unknown to the investigator and the participant, all participants were asked to guess in which condition they had been. At the end of the experiment, participants were debriefed.

Data Analysis

Investment decisions were analyzed using a mixed-design ANOVA with prior investment (no vs. low vs. high), costs (low vs. high) and probability of success (low vs. medium vs. high) as within-subject factors and stimulation condition (anodal vs. cathodal vs. sham) as between-subject-factor. Significant main or interaction effects were further pursued by Bonferroni-corrected post-hoc tests. All reported p-values are two-tailed.

Sunk-cost score: In line with our previous study (Haller and Schwabe 2014), we calculated a sunk-cost score for each participant based on their investment decisions. We calculated the individual differences in the percentage of investment decisions between "no prior investment trials" and "low prior investment trials" as well as the difference between "low prior investment trials" and "high prior investment trials" for all six combinations of project costs and probability of success. The average of these difference scores was used as a single estimate for the individual "sunk-cost tendency". A high sunk-cost score indicates large differences between the trial types and thus a stronger sunk cost tendency.

Results

Overall, participants were unable to distinguish the different stimulation types. Treatment guesses were at chance level (58%) and did not differ between stimulation conditions (χ^2_2 = 1.78, P = .41).

Anodal stimulation over the dlPFC boosts the sunk-cost bias

As expected, participants' investment decisions were strongly influenced by the expected value of an option, as indicated by significant main effects of costs ($F_{1,57}$ = 78.44, P < .001, partial η^2 = .58) and probability of success ($F_{1.41,80.58}$ = 160.75, P < .001, partial η^2 = .74) as well as a costs × probability of success interaction ($F_{1.33,76.05}$ = 12.68, P < .001, partial η^2 = .18). Critically, our data also demonstrate a pronounced sunk-cost effect: participants' decisions to invest or not invest were significantly influenced by whether they had already made an investment or not (main effect prior investment: $F_{1.79,102.00}$ = 93.16, P < .001, partial η^2 = .62). This tendency to invest more after a prior investment held for both trials where the prior investment was low or high (low- vs. no prior investment and high- vs. no prior investment: both P < .001; low- vs. high prior investment: P = .99). As shown in Figure 2a-c, the impact of prior investments was strongest for options with low expected value and the influence of the expected value on decision making was significantly modulated by prior investments (costs × probability of success × prior investment interaction: $F_{3.23,183.89}$ = 4.10, P = .003, partial η^2 = .07).

Most importantly, however, the tendency to continue investing in a project that had already been invested in (i.e., the sunk-cost effect) was significantly affected by tDCS over the dlPFC (stimulation × prior investment: $F_{3.58,102.00}$ = 5.99, P < .001, partial η^2 = .18). When participants had not yet invested in a project, stimulation over the dlPFC did not alter their decision-making (main effect of stimulation in no prior investment trials: $F_{2,57}$ = .44, P = .65, partial η^2 = .02) and choices were exclusively driven by the expected value of the current project (see increase in bars in Fig. 2a from left to right; cost × probability of success interaction for no prior investment trials only: $F_{1.78,57}$ = 5.87, P = .004, partial η^2 = .09). However, when participants had already made a low investment, stimulation over the dlPFC altered their decision behavior significantly (main effect of stimulation in low prior investment trials: $F_{2,57}$ = 4.81, P = .012, partial η^2 = .14): Anodal stimulation led to higher investment rates than sham stimulation (P < .009), but there was no such effect for cathodal stimulation (P = .36). When participants had already made a large investment, anodal stimulation over the dlPFC led to higher investment rates (main effect of stimulation in high prior investment trials: $F_{2,57}$ = 6.96, P = .002, partial η^2 = .20) compared to both sham stimulation (P = .006) and cathodal stimulation (P = .007), whereas the latter two conditions did not differ (P = .99).

The costs × probability of success × prior investment × stimulation interaction did not reach statistical significance ($F_{425.59,\ 183,89}$ = 1.20, P = .31, partial η^2 = .04). However, the data displayed in figure 2 clearly suggest that anodal stimulation over the dlPFC affected most strongly choices about options with low expected value. We therefore performed an additional post-hoc ANOVA with the factors expected value (high costs/low probability of success vs. low costs/high probability of success) × prior investment × stimulation, for the options with the lowest and highest expected value only. This analysis confirmed that the modulatory influence of anodal stimulation indeed depended on the expected value of the option (expected value × prior investment × stimulation interaction: $F_{3.94,\ 110,99}$ = 2.79, P = .03, partial η^2 = .09). Specifically, anodal stimulation increased the impact of prior investments for options with low expected value (prior investment × stimulation interaction: $F_{3.97,\ 113,02}$ = 3.96, P = .005, partial η^2 = .12) but not for projects with high expected value (prior investment × stimulation interaction: $F_{4,\ 114}$ = 0.56, P = .69, partial η^2 = .02), perhaps reflecting that most participants decided to invest in these projects anyway.

Additionally, we calculated a sunk-cost score as a single parameter that reflected the individual sunk-cost tendency. As displayed in Figure 3, stimulation over the dlPFC significantly affected participant's sunk cost tendency ($F_{2,57} = 6.68$, $P = .002$, partial $\eta^2 = .19$): Anodal dlPFC-stimulation resulted in a significantly higher sunk-cost score than both cathodal ($P = .034$) and sham stimulation ($P = .003$), which did not differ ($P = .99$).

The analyses reported so far only focused on the expected value and the investments in the current trial. In order to test whether choices, investments, and outcomes in previous trials had an influence on decisions in the current trial, we performed a logistic regression analysis in which the parameters from the *previous* trials (i.e. previous choice, previous amount invested, and previous outcome) were included as regressors, in addition to the costs, probability, and prior investment in the current trial as well as the tDCS condition and the prior investment × tDCS condition interaction. This analysis showed that participants' decisions were indeed influenced by choices (B = .58, p <. 001), investments (B = .11, $p = .03$), and outcomes (B = -.12, $p = .01$) on the previous trial: when participants had invested in the previous trial, they were more likely to invest in the current trial; when they had made a larger investment in the previous trial, they were more likely to accept higher costs in the current trial; and losses on the previous trial appeared to motivate participants to invest in the current trial. Critically, however, the effect of the prior investment in the current trial (i.e., the sunk cost effect) and the prior investment × tDCS condition interaction remained significant (both B > 1.34, both $p < .001$) when the parameters of the previous trial were included in the analysis, indicating that the specifics of the previous trial cannot explain the observed effects.

Control variables

We compared participants in the three stimulation groups in a whole range of control variables, to ensure that they did not differ with respect to their behavioral inhibition, drive, fun seeking and reward responsiveness (as measured by the BIS/BAS), their neuroticism, extraversion, openness and agreeableness (as measured by the NEO FFI), their impulsiveness (as measured by the BIS-15) or their desire not to appear wasteful (as measured by the sunk cost questionnaire). There were no such differences for all but one variable (all $F < 2.9$, all $P > .05$): Only for the NEO scale conscientiousness, there was a significant group difference ($F_{2,57} = 5.81$, $P < .01$, partial $\eta^2 = .17$) indicating that participants in the anodal group were less conscientious than those in the cathodal and sham condition (both $P < .05$). Thus, we performed our analyses again with conscientiousness as a covariate. Importantly, however, including conscientiousness did not alter our findings, indicating that group differences in conscientiousness could not explain our results. In particular, the significant prior investment × stimulation interaction remained ($F_{3.61,100.96} = 6.82$, $P < .001$, partial $\eta^2 = .20$) and none of the effects including the covariate conscientiousness approached significance (all $P > .14$). Please note that we did not find any correlations between the individual norm not to waste resources and the sunk cost-effect (all $r > -.08$ and $< .11$, all $p > .65$), which is most likely due to the fact that we externally manipulated the brain area representing this norm using tDCS thus changing its influence on choice behavior but not necessarily the participant's awareness of the norm (Knoch et al. 2006; Ruff et al. 2013).

Finally, given that previous studies reported sex differences in cognitive functions (Cahill 2006) we tested for possible gender effects by including the participants' gender as an additional factor in our analyses. Yet, we did not find any significant main or interaction effects (all $F < 1.95$, all $p > .12$), indicating that men and women did not differ in task performance, the sunk-cost tendency, or the impact of tDCS. Moreover, including participants' gender as a factor did not change any of the other significant results reported above.

Discussion

The sunk-cost effect is one of the most fundamental biases in human decision making and has been proposed to underlie a wide range of behaviors, including the decisions to stay in a failing relationship (Strube 1988), not to leave a dissatisfying job (Arkes and Blumer 1985), or to adhere to failing policies (Staw 1976). In the present experiment, we sought to elucidate the neural mechanisms underlying the sunk-cost effect. More specifically, we employed tDCS over the right dlPFC during an investment task in order to assess the role of the stimulated brain area in people's tendency to consider prior investments during decision-making. We found that anodal stimulation over the right dlPFC indeed increased the impact of past investments on current decision-making, thus leading to a more pronounced sunk-cost effect. This effect could not be attributed to individual differences in personality traits, such as impulsiveness, and it did not occur after sham or cathodal stimulation.

Our data are consistent with the view that the dlPFC plays an important role in the sunk-cost effect. In addition, the present findings support a model in which the dlPFC implements the norm not to be wasteful, which then counteracts decision-making based solely on expected values. The dlPFC is generally thought to influence decision-making by bringing abstract rules and norm-based-behavior into action (Sanfey 2003; Koechlin and Summerfield 2007; Baumgartner et al. 2011; Crockett et al. 2013; Ruff et al. 2013). In line with this view, recent fMRI data showed that the activity of the dlPFC is related to the individual norm not to waste resources, which is one of the major sources of the sunk-cost effect (Arkes and Blumer 1985) and which is itself associated with an increased sunk-cost tendency (Haller and Schwabe 2014). Alternatively, the increased sunk-cost effect after anodal stimulation over the dlPFC may have been due to a more general influence on working memory processes required for the present task. In primates, dlPFC cells code for both choices and outcomes not only of the current trial, but also of past trials (Seo et al. 2007) and the key role of the dlPFC in working memory in general has been well-established (Fuster and Alexander 1971; Jonides et al. 1993; Curtis and D'Esposito 2003). Stimulation over the dlPFC might thus have led to a more pronounced sunk-cost effect by amplifying representations of previous investments in working memory. On the other hand, implementing social norms such as the norm not to waste resources may resemble a resourceful top-down control process that helps us to incorporate the rules of our social environment in our decisions. Anodal stimulation over the dlPFC may have over-activated this abstract rule, thus impeding value-based decision making. However, these alternatives are not mutually exclusive. After all, in order to be an effective top-down influence, any social norm needs to be represented in working memory.

Importantly, however, anodal stimulation over the dlPFC did not affect decision-making when participants had not yet invested in a project. Moreover, if participants had not yet made an investment, decision-making in the anodal tDCS group was mainly based on the expected value of an option, exactly as for the other experimental groups. Thus, our findings clearly show that dlPFC stimulation neither affected decision-making in general nor rendered decision-making based on expected values impossible. Rather, the impact of anodal stimulation over the dlPFC was specific to situations when prior investments had triggered top-down regulation processes, presumably related to activating the norm not to waste resources or working memory processes.

Although anodal stimulation over the dlPFC had a critical impact on the strength of the sunk-cost effect, it is in our view unlikely that the dlPFC drives this effect in isolation. Instead, our data are consistent with the hypothesis that dlPFC stimulation may have altered the crosstalk of the dlPFC with other areas critical for decision-making, in particular the vmPFC. The vmPFC is a key structure for value-based decision-making (Tom et al. 2007; Grabenhorst and Rolls 2011) and our previous data indicate that prior investments enhance the interaction of dlPFC and vmPFC, resulting in a decrease of vmPFC activity (Haller and Schwabe 2014). When activated by relevant past investments, the dlPFC may override vmPFC activity and thus hamper decision-making based on the current value of an option. Such a modulating influence of the dlPFC on vmPFC activity has also been suggested by other studies examining other types of decisions (Hare et al. 2009; Baumgartner et al. 2011). Thus, our data lead to the interesting proposal for future studies that anodal stimulation targeting at the dlPFC may modulate the interplay of prefrontal areas with areas involved in valuation, in a manner that biases decision-making towards rather abstract norms at the expense of 'rational' decision-making based on the actual value of an option. Importantly, while previous findings related this modulatory influence of the dlPFC on the vmPFC to self-control, fostering advantageous decision-making (Hare et al. 2009), the present findings suggest that 'top-down' influences on decision-making are not necessarily beneficial. More specifically, our findings may imply that the over-activation of norms or past investments, represented in the dlPFC, may impede value-based decision-making, depending on the specific demands of a situation.

As expected, the sunk-cost effect was most pronounced for options with low expected value, i.e., for rather disadvantageous options in which participants invested only when they had already made an investment. Moreover, anodal stimulation over the dlPFC increased the influence of prior investments specifically for low expected value options, thus rendering decision-making even more unfavorable. Previous research has suggested that the sunk-cost effect may also be dependent on the amount of resources invested, with higher prior investments leading to a stronger sunk-cost effect (Haller and Schwabe 2014). At least for the option with the lowest expected value, this pattern was also obtained in the present experiment, both after sham and anodal dlPFC stimulation.

TDCS is a safe, non-invasive method that allows assessing the role of cortical brain areas in cognitive processes such as decision-making. It is, however, important to note that the spatial resolution of this method is limited due to the size of the electrodes. Based on our previous fMRI results that identified the dlPFC as the critical area for the sunk-cost effect (Haller and Schwabe 2014), we chose an electrode position (F4 in the standard EEG 10-20 system) that has been used in previous studies that the targeted dlPFC (Fregni et al. 2005; Harty et al. 2014; Zmigrod et al. 2014; Zwissler et al. 2014; Axelrod et al. 2015; Pope 2015). Studies that combined tDCS with fMRI confirmed that stimulation over this (or the contralateral F3) site led to changes in dlPFC activation (Stagg et al. 2013; Weber et al. 2014). Note, however, that the changes in activation were not limited to the dlPFC but also included neighboring and other connected areas. While it cannot be ruled out from a physiological perspective that the stimulation affected also cortices adjacent to the dlPFC, it is important to note that none of these adjacent cortices was activated in our previous fMRI study (Haller and Schwabe 2014). The tDCS effects on the sunk-cost bias observed here are thus highly likely to reflect modulation of task-relevant activity in the dlPFC, rather than in adjacent structures that are known not to be involved in this effect. Finally, it is important to note that in spite of the evidence for physiologically inhibitory influences of cathodal stimulation (Nitsche and Paulus 2000), we did not obtain an effect of cathodal dlPFC on the sunk-cost effect. This lack of behavioral effects for cathodal stimulation appears generally consistent with a whole range of other studies that did not find differences between sham and cathodal stimulation (e.g. Kincses et al. 2004; Marshall et al. 2005; Sparing et al. 2008), and with proposals that the effect of cathodal stimulation may be task-dependent and less reliable than that of anodal stimulation (for a review see Jacobson et al. 2012). Alternatively, the lack of cathodal effects in our study may reflect a floor effect, as the options with low expected value were rarely chosen even in the sham condition. This may have made it difficult to bias choice towards choosing these options even less often. In any case, the lack of behavioral effects in the cathodal condition perfectly controls for any unspecific non-neural effects of the ongoing tDCS and clearly demonstrates that the enhancements of the sunk-cost effect during anodal tDCS reflects the specific neural effects of this intervention.

To conclude, we show here that anodal stimulation over the right dlPFC boosts people's tendency to consider past expenses during current decision-making, suggesting that the stimulated brain area may play a critical role in the sunk-cost effect. Given that this effect leads to increased investments in rather disadvantageous options, these data show that anodal stimulation does not always improve decision-making but may also counteract optimal choices by enhancing a decision-making bias (see also Xue et al. 2011). The present findings shed light on the brain mechanisms underlying the well-known human tendency to continue to 'throw good money after bad', which may have considerable consequences for understanding maladaptive decisions in politics (Staw 1976), financial markets (Murnighan 2002), and in our everyday lives (Arkes and Blumer 1985; Strube 1988).

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References

Arkes H, Hutzel L. 2000. The role of probability of success estimates in the sunk cost effect. J Behav Decis Mak. 13:295-306.

Arkes HR, Ayton P. 1999. The sunk cost and Concorde effects: Are humans less rational than lower animals? Psychol Bull. 125:591.

Arkes HR, Blumer C. 1985. The psychology of sunk cost. Organ Behav Hum Decis Process. 35:124-140.

Axelrod V, Rees G, Lavidor M, Bar M. 2015. Increasing propensity to mind-wander with transcranial direct current stimulation. Proc Natl Acad Sci USA. 112:3314-3319.

Baumgartner T, Knoch D, Hotz P, Eisenegger C, Fehr E. 2011. Dorsolateral and ventromedial prefrontal cortex orchestrate normative choice. Nat Neurosci. 14:1468-1474.

Bechara A, Damasio H, Damasio AR, Lee GP. 1999. Different contributions of the human amygdala and ventromedial prefrontal cortex to decision-making. J Neurosci. 19:5473-5481.

Cabantous L, Gond J-P. 2011. Rational Decision Making as Performative Praxis: Explaining Rationality's Éternel Retour. Organ Sci. 22:573-586.

Cahill L. 2006. Why sex matters for neuroscience. Nat Rev Neurosci. 7:477-484.

Carver CS, White TL. 1994. Behavioral inhibition, behavioral activation, and affective responses to impending reward and punishment: the BIS/BAS scales. J Pers Soc Psychol. 67:319.

Crockett MJ, Braams BR, Clark L, Tobler PN, Robbins TW, Kalenscher T. 2013. Restricting temptations: Neural mechanisms of precommitment. Neuron. 79:391-401.

Curtis CE, D'Esposito M. 2003. Persistent activity in the prefrontal cortex during working memory. Trends Cogn Sci. 7:415-423.

Davis NJ. 2014. Transcranial stimulation of the developing brain: a plea for extreme caution. Front Hum Neurosci. 8.

De Martino B, Kumaran D, Seymour B, Dolan RJ. 2006. Frames, biases, and rational decision-making in the human brain. Science. 313:684-687.

Delgado MR, Dickerson KC. 2012. Reward-related learning via multiple memory systems. Biol Psychiatry. 72:134-141.

Edwards W. 1954. The theory of decision making. Psychol Bull. 51:380.

Frank RH, Bernanke B. 2006. Principles of Microeconomics. New York (NY): McGraw-Hill.

Fregni F, Boggio PS, Nitsche M, Bermpohl F, Antal A, Feredoes E, Marcolin MA, Rigonatti SP, Silva MT, Paulus W. 2005. Anodal transcranial direct current stimulation of prefrontal cortex enhances working memory. Exp Brain Res. 166:23-30.

Fuster JM, Alexander GE. 1971. Neuron activity related to short-term memory. Science. 173:652-654.

Garland H. 1990. Throwing good money after bad: The effect of sunk costs on the decision to esculate commitment to an ongoing project. J Appl Psychol. 75:728.

Gold JI, Shadlen MN. 2007. The neural basis of decision making. Annu Rev Neurosci. 30:535-574.

Grabenhorst F, Rolls ET. 2011. Value, pleasure and choice in the ventral prefrontal cortex. Trends Cogn Sci. 15:56-67.

Haller A, Schwabe L. 2014. Sunk costs in the human brain. Neuroimage. 97:127-133.

Hare TA, Camerer CF, Rangel A. 2009. Self-control in decision-making involves modulation of the vmPFC valuation system. Science. 324:646-648.

Harty S, Robertson IH, Miniussi C, Sheehy OC, Devine CA, McCreery S, O'Connell RG. 2014. Transcranial direct current stimulation over right dorsolateral prefrontal cortex enhances error awareness in older age. J Neurosci. 34:3646-3652.

Jacobson L, Koslowsky M, Lavidor M. 2012. tDCS polarity effects in motor and cognitive domains: a meta-analytical review. Exp Brain Res. 216:1-10.

Jocham G, Hunt LT, Near J, Behrens TE. 2012. A mechanism for value-guided choice based on the excitation-inhibition balance in prefrontal cortex. Nat Neurosci. 15:960-961.

Jonides J, Smith EE, Koeppe RA, Awh E, Minoshima S, Mintun MA. 1993. Spatial working-memory in humans as revealed by PET. Nature. 363:623-625.

Kable JW, Glimcher PW. 2007. The neural correlates of subjective value during intertemporal choice. Nat Neurosci. 10:1625-1633.

Kahneman D, Knetsch JL, Thaler RH. 1991. Anomalies: The endowment effect, loss aversion, and status quo bias. J Econ Perspect. 5:193-206.

Kennerley SW, Walton ME, Behrens TE, Buckley MJ, Rushworth MF. 2006. Optimal decision making and the anterior cingulate cortex. Nat Neurosci. 9:940-947.

Kincses TZ, Antal A, Nitsche MA, Bártfai O, Paulus W. 2004. Facilitation of probabilistic classification learning by transcranial direct current stimulation of the prefrontal cortex in the human. Neuropsychologia. 42:113-117.

Knoch D, Pascual-Leone A, Meyer K, Treyer V, Fehr E. 2006. Diminishing reciprocal fairness by disrupting the right prefrontal cortex. Science. 314:829-832.

Koechlin E, Summerfield C. 2007. An information theoretical approach to prefrontal executive function. Trends Cogn Sci. 11:229-235.

Leotti LA, Delgado MR. 2014. The value of exercising control over monetary gains and losses. Psychol Sci. 25:596-604.

Marshall L, Mölle M, Siebner HR, Born J. 2005. Bifrontal transcranial direct current stimulation slows reaction time in a working memory task. BMC Neurosci. 6:23.

McCrae RR, Costa PT. 2004. A contemplated revision of the NEO Five-Factor Inventory. Pers Individ Dif. 36:587-596.

Murnighan JK. 2002. A very extreme case of the dollar auction. J Manag Educ. 26:56-69.

Nitsche MA, Cohen LG, Wassermann EM, Priori A, Lang N, Antal A, Paulus W, Hummel F, Boggio PS, Fregni F. 2008. Transcranial direct current stimulation: state of the art 2008. Brain Stimul. 1:206-223.

Nitsche MA, Doemkes S, Karakoese T, Antal A, Liebetanz D, Lang N, Tergau F, Paulus W. 2007. Shaping the effects of transcranial direct current stimulation of the human motor cortex. J Neurophysiol. 97:3109-3117.

Nitsche M, Paulus W. 2000. Excitability changes induced in the human motor cortex by weak transcranial direct current stimulation. J Physiol. 527:633-639.

Pope PA, Brenton JW, Miall RC. 2015. Task-Specific Facilitation of Cognition by Anodal Transcranial Direct Current Stimulation of the Prefrontal Cortex. Cereb Cortex. 2015:bhv094.

Rangel A, Camerer C, Montague PR. 2008. A framework for studying the neurobiology of value-based decision making. Nat Rev Neurosci. 9:545-556.

Ruff CC, Fehr E. 2014. The neurobiology of rewards and values in social decision making. Nat Rev Neurosci. 15:549-562.

Ruff CC, Ugazio G, Fehr E. 2013. Changing social norm compliance with noninvasive brain stimulation. Science. 342:482-484.

Rushworth MF, Noonan MP, Boorman ED, Walton ME, Behrens TE. 2011. Frontal cortex and reward-guided learning and decision-making. Neuron. 70:1054-1069.

Samuelson W, Zeckhauser R. 1988. Status quo bias in decision making. J Risk Uncertainty. 1:7-59.

Sanfey AG, Rilling JK, Aronson JA, Nystrom LE, Cohen JD. 2003. The neural basis of economic decision-making in the ultimatum game. Science. 300:1755-1758.

Shafir E, Simonson I, Tversky A. 1993. Reason-based choice. Cognition. 49:11-36.

Sparing R, Dafotakis M, Meister IG, Thirugnanasambandam N, Fink GR. 2008. Enhancing language performance with non-invasive brain stimulation—a transcranial direct current stimulation study in healthy humans. Neuropsychologia. 46:261-268.

Spinella M. 2007. Normative data and a short form of the Barratt Impulsiveness Scale. Int J Neurosci. 117:359-368.

Stagg CJ, Lin RL, Mezue M, Segerdahl A, Kong Y, Xie J, Tracey I (2013) Widespread modulation of cerebral perfusion induced during and after transcranial direct current stimulation applied to the left dorsolateral prefrontal cortex. J. Neurosc. 33:11425-11431.

Staw BM. 1976. Knee-deep in the big muddy: A study of escalating commitment to a chosen course of action. Organ Behav Hum Perf. 16:27-44.

Strube MJ. 1988. The decision to leave an abusive relationship: empirical evidence and theoretical issues. Psychol Bull. 104:236.

Tom SM, Fox CR, Trepel C, Poldrack RA. 2007. The neural basis of loss aversion in decision-making under risk. Science. 315:515-518.

Tversky A, Kahneman D. 1974. Judgment under uncertainty: Heuristics and biases. Science. 185:1124-1131.

van Putten M, Zeelenberg M, van Dijk E. 2010. Who throws good money after bad? Action vs. state orientation moderates the sunk cost fallacy. Judgm Decis Mak. 5:33-36.

Weber MJ, Messing SB, Rao H, Detre JA, Thompson-Schill SL (2014) Prefrontal transcranial direct current stimulation alters activation and connectivity in cortical and subcortical reward systems: A tDCS-fMRI study. Hum Brain Mapp. 35:3673-3686.

Xue G, Lu Z, Levin IP, Bechara A (2011) An fMRI study of risk-taking following wins and losses: Implications for the gambler's fallacy. Hum Brain Mapp. 32:271-281.

Zmigrod S, Colzato LS, Hommel B. 2014. Evidence for a Role of the Right Dorsolateral Prefrontal Cortex in Controlling Stimulus-response Integration: A Transcranial Direct Current Stimulation (tDCS) Study. Brain Stimul. 7:516-520.

Zwissler B, Sperber C, Aigeldinger S, Schindler S, Kissler J, Plewnia C. 2014. Shaping memory accuracy by left prefrontal transcranial direct current stimulation. J Neurosci. 34:4022-4026.

Figure captions:

Figure 1. The investment task. On each trial, participants were presented with a project characterized by its costs (low vs. high) and its probability of success (low vs. medium vs. high). Participants were instructed to decide whether they want to invest the depicted costs in the project. If they decided to invest, they either received immediate feedback about the project's success (no prior investment trials) or were told, that additional investments would be necessary (low- and high prior investment trials). In the latter case, participants were presented with the additional costs and the updated probabilities of success for the project. The no-, low- and high prior investment trials differed only in whether and how much participants had already invested in the project.

Figure 2. Participants' investment decisions depend on prior investments and dlPFC stimulation. Participants' decisions to invest generally reflected the expected value of an option. However, the influence of the expected value decreased significantly when participants had already made an investment (b and c), indicating a sunk-cost effect. Anodal stimulation of the dlPFC led to a more pronounced sunk-cost effect, as evident in significantly more choices to invest in trials with low or high prior investments; this effect appeared to be most pronounced for projects with low expected value. When participants had not yet invested in a project (a), anodal stimulation did not alter decision behavior. Cathodal or sham stimulation did not alter decision-making. *$P < .05$, **$P < .01$. P-values are corrected for multiple comparisons.

Figure 3. Impact of dlPFC stimulation on the sunk cost score. The sunk cost score was calculated as a single index of the subjects' tendency to consider past investments in current decisions. A higher score indicates a more pronounced sunk-cost effect. Anodal stimulation

led to a higher sunk cost score than both cathodal and sham stimulation. *$P < .05$, **$P < .01$. P-values are corrected for multiple comparisons.

Figure 1

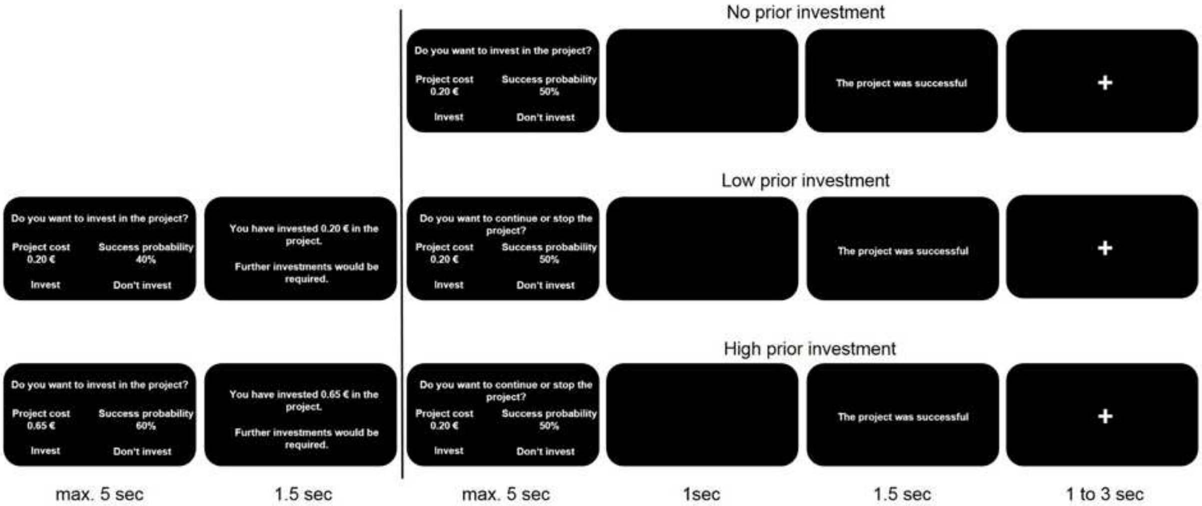
No prior investment
Low prior investment
High prior investment
Do you want to invest in the project?
Project cost 0.20 €
Success probability 40%
Invest
Don't invest
You have invested 0.20 € in the project.
Further investments would be required.
Do you want to invest in the project?
Project cost 0.65 €
Success probability 60%
Invest
Don't invest
You have invested 0.65 € in the project.
Further investments would be required.
Do you want to invest in the project?
Project cost 0.20 €
Success probability 50%
Invest
Don't invest
Do you want to continue or stop the project?
Project cost 0.20 €
Success probability 50%
Invest
Don't invest
The project was successful
+
max. 5 sec
1.5 sec
max. 5 sec
1sec
1.5 sec
1 to 3 sec

Figure 2

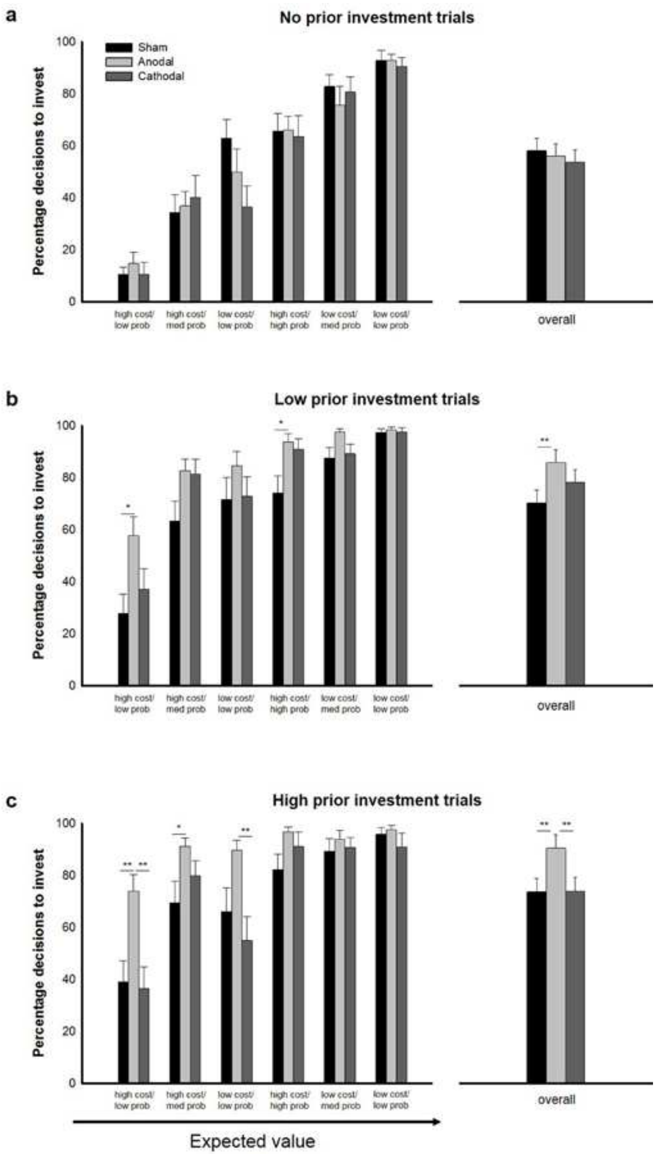
a
No prior investment trials
Sham
Anodal
Cathodal
Percentage decisions to invest
0
20
40
60
80
100
high cost/ low prob
high cost/ med prob
low cost/ low prob
high cost/ high prob
low cost/ med prob
low cost/ low prob
overall
b
Low prior investment trials
Percentage decisions to invest
high cost/ low prob
high cost/ med prob
low cost/ low prob
high cost/ high prob
low cost/ med prob
low cost/ low prob
overall
c
High prior investment trials
Percentage decisions to invest
high cost/ low prob
high cost/ med prob
low cost/ low prob
high cost/ high prob
low cost/ med prob
low cost/ low prob
overall
Expected value

Figure 3