High-definition tDCS alters impulsivity in a baseline-dependent manner

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a r t i c l e i n f o

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a b s t r a c t

In intertemporal choice (ITC), people discount future rewards in proportion to the time delay until re-

mixed results have been reported in terms of hemisphere laterality (Cho et al., 2010, 2012; Essex et al., 2012; Figner et al., 2010). Similarly, bilateral transcranial direct current stimulation (tDCS) of the prefrontal cortex in delay discounting also yielded opposing effects on impulsivity change (Hecht et al., 2013; Kekic et al., 2014).

To address these conflicted findings, we systematically manipulated dlPFC activity using high-definition tDCS (HD-tDCS) in addition to conventional tDCS during an intertemporal choice task. We recruited three separate cohorts of subjects and applied conventional tDCS, HD-tDCS anodal, and HD-tDCS cathodal to each cohort. Subjects within each cohort received lateralized brain stimulation and sham stimulation on three different visits in a randomized order. Our design allowed us to replicate and extend previous conventional tDCS results (Hecht et al., 2013). In particular, by orthogonalizing stimulation site (left versus right dlPFC) and stimulation polarity (anodal versus cathodal) while using HD-tDCS, we exhaustively interrogated the functional specificity of dlPFC in ITC. We conjectured that brain stimulation to the left and right dlPFC would have asymmetric effects due to functional segregation of hemispheric laterality. Different stimulation polarities (anodal or cathodal) would have different modulation effects on neural activity (excitation or inhibition) (Filmer et al., 2014; Jacobson et al., 2012). Furthermore, the recruitment of subjects along the wide range of the impulsivity spectrum allowed us to test whether tDCS changes subjects' impulsivity in a homogeneous manner. Lastly, we also tested whether dlPFC was differentially involved in arbitrating reward options in immediate and delayed contexts. In the immediate context, one reward option in the choice set was available immediately and the alternative was delayed, while in the delayed context, both options were delayed. Given the hypothesized role of dlPFC in exerting self-control in ITC when immediate rewards are involved (Figner et al., 2010), we expected that dlPFC modulation might have different effects in the immediate and delayed contexts.

Materials and methods

Participants

117 healthy adults were recruited into 3 separate tDCS experiments (39 in each experiment; Exp. 1: 24 males, age 22.1 ± 2.0 years; Exp. 2A: 18 males, age 21.1 ± 1.8 years; Exp. 2B: 21 males, age 21.4 ± 2.0 years). All participants were right-handed and had no prior experience with tDCS (conventional or HD). None of the participants had a history of neurological or psychiatric problems. All participants gave informed written consent. Participants were paid based on their task performance (see details below). The study was approved by the Ethics Committee of the School of Psychological and Cognitive Sciences, Peking University.

Experimental design and procedure

This study employed a randomized within-subject crossover design; participants in the three experiments completed three sessions of intertemporal choice tasks (Fig. 1A) under different types of tDCS manipulation of dlPFC. Each experimental session was separated by approximately 24 h. For each session, subjects completed 144 trials (12 blocks of 12 trials each). During each trial, participants were asked to make a choice between a sooner-smaller (SS) reward and a later-larger (LL) reward. The left-right positions of two options on the computer screen were randomized across trials, and participants were instructed to respond within 5 s. After responding, the chosen item was highlighted with a red rectangle. If participants failed to respond within 5 s, a warning sign reading, "Please respond faster" was displayed, and the task proceeded to the next trial (missed trials < 2% for each participant).

The ITC task incorporated two different contexts that differed in the delay to the SS rewards. The first context was the "immediate context"

$$SV = LL\ Amo_{\iota}\ n\ /(1 + kD)$$

Results

Experiment 1. In the immediate context, choices were made be-

Previous research using TMS suggests that dlPFC influences intertemporal decision-making only for choices involving immediate rewards (Figner et al., 2010). To systematically test for such an effect with tDCS, we included choice tasks under the delayed context in the experiments, in which both the SS and LL outcomes were delayed at least 30 days. We estimated each subject's indifference points at each delay interval, and we also estimated each participant's discount rate using the ASAP model (Kable and Glimcher, 2010) in the delayed context. Additionally, we compared subjects' indifference points and discount rates

and tDCS studies in humans have begun to unravel the causal link between dlPFC activity and intertemporal decision-making (Cho et al., 2010; Essex et al., 2012; Figner et al., 2010; Hecht et al., 2013; Kekic et al., 2014). However, results from these studies are mixed in terms of laterality of dlPFC function and the effects of different types of stimulation.

In the current study, we adopted a conventional tDCS protocol in Exp. 1, but we did not replicate the results of Hecht D ,,

change equivalently, resulting in invariant relative value differences and hence no change in preference. Another possibility is that dlPFC may carry out a self-control function that is not required for decisions involving two delayed rewards (Figner et al., 2010; Hare et al., 2010).

Conclusion

We provide direct evidence in establishing a causal link between HD-tDCS manipulated left dlPFC activity and significant behavioral change in intertemporal decision-making where immediate reward was involved. Anodal and cathodal HD-tDCS induced decreased and increased intertemporal discount rates, respectively. These mirroring effects depended on subjects' baseline impulsivity, such that participants with lower baseline impulsivity experienced greater relative change during left dlPFC inhibition. Our results might inform future neural models of ITC by providing a clear demonstration of the causal role of left dlPFC. The baseline dependent manner of the dlPFC manipulation effect also yields insight into why dlPFC manipulation biases behaviors in some cases but not in others (Otto et al., 2013; Weber et al., 2004).

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at http://dx.doi.org/10.1016/j.neuroimage.2016.09.006.

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