



Transcranial alternating current stimulation affects decision making

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A commentary on

Transcranial alternating current stimulation increases risk-taking behavior in the balloon analog risk task

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Neuromodulation by non-invasive brain stimulation such as Transcranial Magnetic Stimulation (TMS) and transcranial Direct Current Stimulation (tDCS) has gained relevance among cognitive neuroscience research. This is mainly due to the possibility of inducing reversible facilitatory or inhibitory effects on cognitive processes (Wagner et al., 2007). TMS and tDCS act through different mechanisms. While TMS depolarizes cortical neurons and induces synaptic long-term changes (Rossi et al., 2009), tDCS polarizes membrane potential according to stimulation polarity (Priori et al., 1998). Both techniques produce regional-specific, state-dependent changes on task performance which may persist after the stimulation period (Nitsche and Paulus, 2001; Rossi and Rossini, 2004).

Here, we aim to discuss an emerging neuromodulatory approach, transcranial Alternating Current Stimulation (tACS). tACS shares the same settings of tDCS in terms of device and montage, but differs in terms of current flow wave-form delivered through the scalp. Unlike tDCS, tACS delivers electrical oscillatory currents at different frequency ranges according to the operator's demands. Recent studies have shown that tACS may boost brain activity related to different functions (Marshall et al., 2006; Feurra et al., 2011a,b), presumably by entraining the ongoing oscillatory activity in a frequency-dependent manner (Thut and Miniussi, 2009). Oscillatory activity of cortical areas engaged in specific cognitive processes synchronizes at distinct frequencies during task performance, ranging from theta

to the gamma band (Varela et al., 2001). This resonance-like interplay between *externally applied* and *internally generated* regional oscillatory activity may prove a powerful approach to manipulate brain activity. So far, investigations of tACS effects on cognitive performance have been limited to visual and somatosensory perception (Feurra et al., 2011b), and motor control (Pogosyan et al., 2009; Feurra et al., 2011a). There is thus an emergent need to test tACS effects on higher cognitive functions.

In a recent paper in *Frontiers in Decision Neuroscience*, Sela et al. (2012) used tACS to investigate the effects of oscillatory prefrontal theta stimulation, a frequency involved in regulatory control during decision making processes. Subjects performed a modified version of the Balloon Analog Risk Task (BART; Lejuez et al., 2004). In this task, volunteers pump a balloon without knowing when it will explode. The more the pump button is pressed, the more points accumulate while at the same time the risk of losing points with a balloon explosion increases. Subjects are thus pressured to decide whether to adopt a risky behavior and keep pumping, or to use a more conservative strategy and stop. tACS was delivered to three groups of healthy volunteers. One group received stimulation over the left prefrontal cortex (lPFC), one over the right prefrontal cortex (rPFC), and the other received sham stimulation. tACS was delivered online during the task. Stimulation started 5 min before the task began and lasted for approximately 10 min until the BART was completed. Crucially, active tACS was only delivered at a theta frequency of 6.5 Hz. Sham stimulation involved the same parameters, but was only delivered for 30 s. Results showed a striking effect of lPFC stimulation, whereas rPFC and sham stimulations failed to produce any considerable effect on task performance. More specifically, the increase of sequential losses during tACS stimulation over lPFC suggested that volunteers lost the

ability to adjust their actions based on negative feedback. Sela et al. (2012) hypothesized that theta stimulation of the lPFC interfered with volunteers' performance during the task, making them more inclined to adopt a risky behavior.

After Marshall et al. (2006), the study by Sela et al. (2012) is the second to show tACS effects on higher cognitive functions and therefore its results are intriguing and improve current knowledge of tACS modulatory effects on behavior. Moreover, this work provides relevant information on the regional specificity of tACS. tACS generally employs medium-to-large sized electrodes (from 3 × 2 to 7 × 5 cm), therefore its focality has been object of debate. By testing different groups for site of stimulation, authors ensured tACS regional specificity, at least regarding left/right PFC function.

However, the experimental design limits the interpretation of the findings. The authors applied only one stimulation frequency. As a consequence, the frequency-specificity of tACS effects on decision making cannot be addressed, and the potential of frequency resolution of tACS is underpowered (Thut and Miniussi, 2009). It would have been of a great interest to use different stimulation frequencies. In this respect, it is worth noticing that also alpha and beta oscillatory activity recorded over prefrontal areas is related to risky decision making processes and reward responsiveness (Pizzagalli et al., 2005; Schutter and van Honk, 2005; Minati et al., 2012). One could hypothesize that, if more stimulation frequencies such as the upper alpha dominant in the rPFC (Pizzagalli et al., 2005) – were used, additional effects of rPFC stimulation on BART performance would have emerged.

The interpretation of the findings in terms of entrainment put forward by Sela et al. (2012) also deserves more caution. The authors suggested that their findings may indicate an entrainment of oscillatory activity in the theta frequency. The

authors cite the work by Zaehle et al. (2010) as direct physiological evidence of tACS entrainment. However, Zaehle et al. (2010) recorded EEG prior and post-tACS application, thereby not providing real online tACS/EEG evidence of entrainment. The mechanisms underlying tACS effects on behavior are still poorly understood, and any solid interpretation of tACS effects in terms of entrainment is premature at this stage. More studies are needed to conclude that tACS entrains oscillatory activity above and beyond a frequency-dependent effect. This is a challenging question for future developments of tACS-EEG co-registration.

Despite its interpretative limitations, the study by Sela et al. (2012) will be of considerable impact for future tACS studies on higher cognition. Frequency- and state-dependent effects of tACS have been demonstrated in several studies (Marshall et al., 2006; Feurra et al., 2011b). Recently, it has been demonstrated that also rhythmic TMS can induce entrainment at specific frequencies (Thut et al., 2011). Now there is need of online tACS/EEG evidence to open a new frontier in oscillatory brain rhythms investigations.

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