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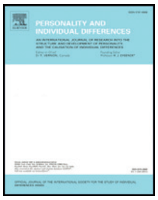

The influence of transcranial alternating current stimulation (tACS) on fluid intelligence: An fMRI study

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ABSTRACT

The past decades have witnessed a huge interest in uncovering the neural bases of intelligence (e.g., Stelmack, & Houlihan, 1995; Stelmack, Knott, & Beauchamp, 2003). This study investigated the influence of transcranial alternating current stimulation (tACS) on fluid intelligence performance and corresponding brain activation. Previous findings showed that left parietal theta tACS leads to a transient increase in fluid reasoning performance. In an attempt to extend and replicate these findings, we combined theta tACS with fMRI. In a double-blind sham-controlled experiment, $N = 20$ participants worked on two intelligence tasks (matrices and paper folding) after theta tACS was applied to the left parietal cortex. Stimulation-induced brain activation changes were recorded during task processing using fMRI. Results showed that theta tACS significantly increased fluid intelligence performance when working on difficult items in the matrices test; no effect was observed for the visuo-spatial paper folding test. Whole-brain analyses showed that left parietal brain stimulation was accompanied by lower activation in task-irrelevant brain areas. Complemental ROI analyses revealed a tendency towards lower activation in the left inferior parietal cortex. These findings corroborate the functional role of left parietal theta activity in fluid reasoning and are in line with the neural efficiency hypothesis.

1. Introduction

Intelligence is associated with diverse relevant real-life outcomes such as educational accomplishment, occupational performance, and even health (Deary, 2012). There is a long-standing research tradition to investigate the neural bases of intelligence (e.g., Ertl & Schafer, 1969; Stelmack & Houlihan, 1995). Neurophysiological models of intelligence emphasize the role of the fronto-parietal-network. The *parieto-frontal integration theory* of intelligence (P-FIT; Jung & Haier, 2007) postulates a four-phase information processing model which highlights the importance of frontal and parietal brain areas and the associated communication patterns between those. Another important theory is the *neural efficiency hypothesis*. It posits that more intelligent people use their brain resources more efficiently as compared to less intelligent individuals in terms of lower brain activation (Haier et al., 1988) or faster neural transmission time (Stelmack, Knott, & Beauchamp, 2003). A review of relevant findings by Neubauer and Fink (2009) further suggests that neural efficiency is restricted to tasks of low to moderate task difficulty, whereas highly able individuals may even invest more cortical resources in very difficult tasks (see also, Dunst et al., 2014). More recently, there has been an increasing interest to use and extend our understanding of the brain in attempts to improve intelligence via brain stimulation (Enriquez-Geppert, Huster, & Herrmann, 2013).

1.1. Stimulating intelligence

Due to the social relevance of *gf*, the issue was raised whether there is a way to increase it through training or stimulation. However, recent reviews and meta-analyses come to inconsistent conclusions, either showing that intelligence scores cannot be increased through cognitive training (Haier, 2014; Melby-Lervåg, Monica, & Hulme, 2016), or finding support for the beneficial effect of systematic cognitive training (Au et al., 2015; Karbach & Verhaeghen, 2014). For example, Jaušovec and Jaušovec (2012) reported that working memory training does not only promote performance in a gf task but also changes the associated electrocortical brain activation. One particular issue of the training approach is the missing evidence for transfer effects, which is sometimes challenged by the similarity between assessment and training tasks (Shipstead, Redick, & Engle, 2012). This methodological problem can be circumvented with direct stimulation of brain activation.

Available research mostly used transcranial electrical stimulation (TES; Kuo & Nitsche, 2012), which It involves either direct (tDCS) or alternating current (tACS). TDCS manipulates neuronal activity via depolarization or hyperpolarization of cell membranes. TACS influences cortical activity via EEG frequency-specific oscillatory current. tACS

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leads to EEG-synchronization of neural activity in the respective frequency band, which may facilitate efficient cortical communication patterns (Zaghi, Acar, Hultgren, Boggio, & Fregni, 2010). Much research has focused on stimulation of the dorsolateral prefrontal cortex (DLPFC). For tDCS, DLPFC stimulation was associated with positive effects on cognitive processes such as language, attention, perception, executive functioning, and memory processes (Jacobson, Koslowsky, & Lavidor, 2012; Utz, Dimova, Oppenländer, & Kerkhoff, 2010). For tACS of the DLPFC, Santarnecchi, Polizzotto, Godone, Giovannelli, Feurra et al. (2013) found that gamma stimulation leads to a shortening of (correct) response latencies in a gf task.

A growing number of studies examined left-parietal stimulation effects on working memory and intelligence. Left-parietal tDCS was found to enhance performance in a verbal memory task (Jacobson, Goren, Lavidor & Levy, 2012). For tACS, Pahor and Jaušovec showed that left parietal theta tACS leads to an increase in gf performance and accompanying changes in cortical activation (Pahor & Jaušovec, 2014). The same stimulation setting also increased working memory capacity and a decreased P3 component latency, which could reflect a faster allocation of attention-related cognitive resources (Jaušovec & Jaušovec, 2014).

1.2. Aims of this study

Previous findings showed that left parietal theta tACS leads to a transient increase in fluid reasoning performance (Pahor & Jaušovec, 2014; Jaušovec & Jaušovec, 2014). In an attempt to replicate and extend these findings, we combined theta tACS with fMRI in a double-blind design. Available evidence indicates that left-parietal theta activity might play a causal role for gf-related demands such as executive functioning (Sauseng, Griesmayr, Freunberger, & Klimesch, 2010), working memory capacity (Postle et al., 2006). Neurophysiological stimulation effects are studied by analyzing concurrent brain activation changes with fMRI. Finally, we test the role of task difficulty as a moderating variable in the relationship between brain stimulation and brain activation (Neubauer & Fink, 2009). We expect that left parietal theta stimulation increases fluid intelligence performance (Pahor & Jaušovec, 2014) and affects brain activation in intelligence-related brain areas according to the P-FIT model (Jung & Haier, 2007). Additionally, the neural efficiency hypothesis predicts that increased intelligence performance is associated with reduced activation of brain areas that are not considered central for intelligence (Basten, Stelzel, & Fiebach, 2013; Neubauer & Fink, 2009).

2. Method

2.1. Participants

25 individuals were recruited from a pre-tested pool of participants (Jauk, Benedek, Dunst, & Neubauer, 2013). All participants were right-handed, had normal or corrected-to-normal vision, and no self-reported history of CNS-affecting drugs, mental or neurological diseases. Five participants were excluded due to excessive missing data or failure to complete both test sessions. The final sample hence consisted of 20 participants (11 women; average age = 24.85; *SD* = 3.30). The sample was kept homogeneous with respect to age (18–30 years), intelligence as measured with the intelligence-structure-battery (INSBAT; for details see Dunst et al., 2014; *M* = 106.09; *SD* = 7.34), and educational level (students) to enable a sensitive test of within-subject stimulation effects. Participants did not report any medical treatments or health problems and gave written informed consent. The study was approved by the local ethics committee.

2.2. Design

The study was a double-blind sham-controlled experiment. One experimenter only operated the stimulation device and had no interaction with the participant, whereas another one (who was blind to the stimulation condition) instructed participants. Verum (i.e., active) and sham (i.e., placebo) stimulation conditions varied within subjects in a counterbalanced fashion. The two sessions were separated by 28 days to control for potential influences of different phases of the menstrual cycle (Amin et al., 2006). Dependent variables were performance in the two gf tasks as well as BOLD responses in fMRI.

2.3. Tasks and procedure

The experiment was carried out in two sessions. Participants received a standardized instruction and then either sham or verum tACS was applied for 15 min (see below), followed by a questionnaire about intensity and duration of stimulation induced sensations. After the stimulation, the participants were led to the scanning room where they performed two intelligence tasks. The matrices task was based on the Raven's progressive matrices (RPM; Court & Raven, 1995), slightly modified to the requirements of neurophysiological investigations (Pahor & Jaušovec, 2014). The test consisted of 50 items – 18 easy (set B of the CPM, and APM items 1–3), and 32 difficult (APM items 4 to 35). The 50 test items were divided into two parallel forms each consisting of 25 items (10 easy items; 15 difficult items) which were counterbalanced between the sham/verum conditions. As in the original RPM, items were presented in a fixed sequence reflecting increasing task difficulty. Each trial of the RPM started with a jittered fixation cross period (6–10 s). Then, the item was presented for 6 s (easy items) or 10 s (difficult items) together with four response alternatives depicted below, followed by a 3 s response phase (indicated by red interrogation marks presented under the figure). During this, participants had to press one of four buttons corresponding to the four response options. Total task duration of the RPM scanner task was about 9 min. This modified RPM has been shown to correlate substantially with the WAIS-R ($r = 0.56$) (Jaušovec & Jaušovec, 2012), suggesting that content validity is not impaired by the shorter item presentation time. The cross-form consistency of the modified RPM had been proven in a larger sample ($r_{A,B} = 0.73$; Pahor & Jaušovec, 2014).

As a second intelligence measure, we used the paper folding task (PFT) from the Stanford-Binet test (Cowan et al., 2011). Participants had to judge which of the four presented figures on the right side corresponded to that one on the left side after variable steps of folding and cutting (Jaušovec & Jaušovec, 2012). Again, we used two parallel versions which consisted of 20 items each. Items were presented in a fixed quasi-randomized sequence. For analyses considering task difficulty, these items were divided in to 10 easy and 10 difficult items based on effective task performance. Presentation parameters were the same as for the RPM except that the duration of stimulus presentation was 7 s per item here, and fixation cross period varied randomly from 5 to 9 s. Total duration of the PFT was about 6 min. Again, cross-form consistency of the modified PFT was established in a previous study ($r_{A,B} = 0.71$, Pahor & Jaušovec, 2014). In both tasks (RPM and PFT) a trial was scored as solved when the correct response alternative was selected before timeout. The total duration of the experiment including instruction, stimulation, and scanning was around 65 min.

2.4. Electrical stimulation

We used a battery-operated stimulator system (DC-stimulator plus, Neuroconn, Ilmenau, Germany). The stimulating electrodes (5 × 7 cm) were attached to the scalp using a rubber band placed over the electrode and attached under the chin. This procedure prevented movement of the electrodes during the experiment. The electrodes were covered by saline soaked sponges, which reduced the electrode impedance. Target electrode was placed over the left parietal location (P3), and the return electrode was placed on Cz. This electrode positioning was chosen because of the key role of the left parietal cortex for gf and gf-related functions (e.g., working memory capacity; Jung & Haier, 2007; Cowan et al.,