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The effects of theta transcranial alternating current stimulation (tACS) on fluid intelligence

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A B S T R A C T

The objective of the study was to explore the influence of transcranial alternating current stimulation (tACS) on resting brain activity and on measures of fluid intelligence. Theta tACS was applied to the left parietal and left frontal brain areas of healthy participants after which resting electroencephalogram (EEG) data was recorded. Following sham/active stimulation, the participants solved two tests of fluid intelligence while their EEG was recorded. The results showed that active theta tACS affected spectral power in theta and alpha frequency bands. In addition, active theta tACS improved performance on tests of fluid intelligence. This influence was more pronounced in the group of participants that received stimulation to the left parietal area than in the group of participants that received stimulation to the left frontal area. Left parietal tACS increased performance on the difficult test items of both tests (RAPM and PF&C) whereas left frontal tACS increased performance only on the easy test items of one test (RAPM). The observed behavioral tACS influences were also accompanied by changes in neuroelectric activity. The behavioral and neuroelectric data tentatively support the P-FIT neurobiological model of intelligence.

1. Introduction

Can we improve intelligence? The unanimous answer of researchers is that, to this date, intelligence cannot be raised in a consistent and long-lasting manner (Haier, 2014; Buschkuehl & Jaeggi, 2010; Jensen, 1998; Gottfredson, 1997). Recently, the debate on whether training can increase performance on tests of intellectual ability has once more gained popularity. The discussion was triggered by Jaeggi et al. (2008), who showed that working memory (WM) training increased performance on tests of fluid intelligence (G_f). Cognitive training, which typically targets working memory, reasoning, and executive functions, is the most common form of intervention used to increase performance on tests of intelligence (e.g., Owen et al., 2010; Klingberg, 2010; Morrison & Chein, 2011; Chooi & Thompson, 2012; Colom et al., 2012; Thompson et al., 2013). The reported effects are diverse, showing performance increases (Jaeggi et al., 2008; von Bastian & Oberauer, 2013; Stephenson & Halpern, 2013) or no significant effects (Owen et al., 2010; Chooi & Thompson, 2012; Colom et al., 2012, 2013b; Thompson et al., 2013). Some studies have further shown that these interventions also change brain activation patterns (Jaušovec & Jaušovec, 2012).

Because our brain is the source of intelligent behavior (Kolb & Whishaw, 2009), it could be speculated that interventions aimed directly toward the structure and functional connectivity of the brain would have a more pronounced influence on measures of fluid intelligence. A direct approach might also have a methodological advantage since it can rule out similarity effects between assessment and training tasks and other environmental variables that are difficult to control or exclude. Studies employing direct interventions can be divided into three broad categories: neurofeedback training, pharmacological interventions, and brain stimulation. Several neurofeedback studies have showed a modest positive influence on different tests of cognitive functions such as episodic retrieving (Keizer et al., 2010), mental rotation (Zoefel et al., 2011), music performance (Egner et al., 2004), creativity and ballroom dancing (Gruzelier, 2009), and intelligence tests in a group of individuals with an intellectual disability (Surmeli & Ertem, 2010). It has also been reported that nootropic or cognitive enhancing substances modestly raise the performance of children on nonverbal tests of intelligence (Schoenthaler et al., 2000), have a positive effect on working memory and intelligence tests (Rae, et al., 2003), and increase performance on Raven's Advanced Progressive Matrices (Stough et al., 2011).

A third approach that can influence brain activity directly is the recently rediscovered field of transcranial electrical stimulation (transcranial direct current, and alternating current stimulation—tDCS and tACS). It is assumed that tDCS modulates resting membrane potentials and, via this mechanism, alters spontaneous cortical activity. Anodal tDCS enhances cortical activity and excitability, while cathodal stimulation has the opposite effect (Bindman et al., 1964). On the other hand, tACS is a

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newly developed stimulation technique that modulates cortical activity by affecting neuronal membrane potentials via oscillatory electrical stimulation in specific frequencies. This technique can be used to interact with ongoing rhythmic cortical activities during cognitive processes (Kuo & Nitsche, 2012). It has been suggested that tACS influences brain oscillations via interference or entrainment of ongoing oscillations (Thut & Miniussi, 2009), as demonstrated with rhythmic transcranial magnetic stimulation (rTMS) in the alpha band (Thut et al., 2011). The effectiveness of tACS in modulating oscillatory brain activity was also demonstrated by Zaehle et al. (2010). Stimulation applied at participants' individual EEG alpha frequency (IAF) resulted in an enhancement of the EEG alpha amplitude, indicating that this stimulation method can interfere with ongoing brain oscillations in a frequency-specific manner. In a recent study, Neuling et al. (2013) replicated and extended the findings of Zaehle et al. (2010) by showing that the tACS-induced alpha amplitude enhancement remained present for at least 30 min after stimulation offset.

To our knowledge, just one study has been conducted that investigates the influence of transcranial electrical stimulation on tests of fluid intelligence. Santarnecchi et al. (2013) showed that gamma-band tACS delivered over the left middle frontal gyrus resulted in a shortening of the time required to find the correct solution in a visuospatial abstract reasoning test similar to Raven's matrices (1990). However, reaction time may not serve as a valid indicator of fluid intelligence, especially since the standard application of Raven's matrices has no time limitation. On the other hand, several studies have reported positive influences of tDCS and tACS on tests of cognitive processes related to fluid intelligence, such as working memory performance (Mulquiney et al., 2011; Boggio et al., 2008; Fregni et al., 2006; Polanía et al., 2012; Tseng et al., 2012), the ability to discriminate numerosity (Cappelletti et al., 2013), creativity, and problem solving (Cerruti & Schlaug, 2009; Chi & Snyder, 2011; Dockery et al., 2009; for a review see Kuo & Nitsche, 2012).

The aim of the present study was to explore the influence of different tACS protocols on performance on tests of fluid intelligence and to extend the current understanding of the neuronal underpinnings of intelligence. Fluid intelligence is defined as the capacity to solve novel, complex problems, using operations such as inductive and deductive reasoning, concept formation, and classification. It has also been suggested that G_f represents the influences of biological factors and incidental learning on intellectual development (Cattell, 1971; Horn & Cattell, 1966). Even though the influence of tDCS on higher cognitive functions has been explored to a greater extent than the influence of tACS, we decided to use tACS because of the possibility to investigate the relationship between brain oscillations and performance on tests of fluid intelligence. Synchronized cortical oscillations in different frequency bands have been proposed to be an important mechanism of high-level cognition giving rise to intelligence, for example, theta band activity has been linked to working memory while narrow alpha band frequencies have been related to attention (Klimesch, 2012).

With respect to the waveform and the specific oscillatory frequency used in the present study, two aspects were considered: (1) the established relation between the constructs of WM and intelligence reported in correlational (Buehner et al., 2005; Colom et al., 2008; Oberauer et al., 2008; Martínez et al., 2011) and experimental approaches (for a review see Morrison and Chein, 2011; Rabipour & Raz, 2012); and (2) the relation between working memory processes and neuronal rhythms in the theta band. It has been shown that theta synchronizes during working memory processes and serves as a gating mechanism, providing optimal neural conditions for specific processing (Sauseng et al., 2010). Therefore, theta oscillation was applied in the tACS protocol. In particular, our goal was to examine whether theta tACS can affect power in theta and alpha frequency bands during a subsequent period of rest and during performance on tests of fluid intelligence.

The second tACS protocol variable that was determined prior to conducting the study was location of stimulation (placement of active electrodes). Based on research findings concerning the structure and neuronal origin of intelligence we decided to target left frontal and left parietal brain areas. According to a model proposed by Duncan et al. (2000), psychometric *g* is implemented within the prefrontal cortex, whereas a more recent model claims that intelligence depends on distributed system of functionally specialized fronto-parietal cortical regions (Jung & Haier, 2007). In Duncan's model (Duncan, 2001, 2003; Duncan & Owen, 2000) fluid intelligence mainly derives from a specific frontal brain network (mid-dorsolateral, mid-ventrolateral and dorsal anterior cingulate cortex), which is important for the control of diverse cognitive functions (e.g., executive control, strategy formation, monitoring). Some neuroscience data support this framework, demonstrating the involvement of the prefrontal cortex in performance on tests of intelligence (Roca et al., 2010; Bishop et al., 2008; Gray et al., 2003; Prabhakaran et al., 1997) and executive function (Duncan, 2006; Duncan & Owen, 2000). A recent morphometric study further indicated that structural features of gray matter in the frontal lobes show an overlapping cluster with measures of crystallized and fluid intelligence (Colom et al., 2013a). On the other hand, Jung and Haier (2007) reviewed 37 neuroimaging studies on the structural correlates of intelligence and synthesized their findings into a so-called ‘parieto-frontal integration’ (P-FIT) model of intelligence. This neurobiological model of intelligence emphasizes the importance of frontal and parietal regions and the white matter association tracts that bind these areas into a synchronized system (Jung & Haier, 2007). Indeed, a number of studies have demonstrated the importance of parietal regions in performance on tests of general intelligence with the use of neuroimaging techniques (Lee et al., 2006; Colom et al., 2006; Haier et al., 2004), electroencephalography (Jaušovec & Jaušovec, 2004; Gevins & Smith, 2000), and lesion mapping (Barbey et al., 2012; Gläscher et al., 2009).

Based on previous research on the effects of IAF tACS on alpha power (Zaehle et al., 2010; Neuling et al., 2013) we hypothesized that active theta tACS would increase theta power, but would have no effect on frequencies in the alpha range. Furthermore, we predicted that theta tACS would improve performance on tests of fluid intelligence. In contrast, no improvement in performance would be seen following sham tACS. Increased performance on IQ tests induced by theta tACS would suggest brain activation patterns similar to those observed in highly intelligent individuals. In two EEG studies (Gevins & Smith, 2000; Jaušovec & Jaušovec, 2004) as well as in one fMRI study (Rypma et al., 2006) individuals scoring high on IQ tests displayed less frontal but more parietal cortical activation. Thus, it was predicted that active tACS positioned over parietal brain areas would have a more prominent effect on performance on tests of fluid intelligence than active tACS positioned over frontal brain areas.

2. Method

2.1. Subjects

Individuals participating in the experiment were recruited from a large scale resting (eyes-closed) EEG study. They were selected because their eyes-closed individual alpha peak frequency (IAF), which is needed to determine theta frequency for tACS, and their IQ scores (WAIS-R, Wechsler, 1981), were available. The sample included 28 right-handed individuals (20 females; average age = 20 years and 8 months; SD = 4.35 months) that were assigned to two groups and equalized with respect to IQ: Parietal group ($N = 14$; $M_{IQ} = 105.38$, $SD = 9.25$) and Frontal group ($N = 14$; $M_{IQ} = 105.45$; $SD = 8.93$). The participants had a similar educational background, took no medication, and reported no health problems. Due to artifacts in the resting (eyes-closed) EEG data, 4 individuals were excluded from the resting EEG data analysis ($N = 24$; 16 females; average age = 20 years and 7 months; SD = 5.25 months).