Empirical research

Enhancing vigilance in operators with prefrontal cortex transcranial direct current stimulation (tDCS)

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Abstract

Sustained attention, often referred to as vigilance in humans, is the ability to maintain goal-directed behavior for extended periods of time and respond to intermittent targets in the environment. With greater time-on-task the ability to detect targets decreases and reaction time increases—a phenomenon termed the vigilance decrement. The purpose of this study was to examine the role of dorsolateral prefrontal cortex in the vigilance decrement. Subjects (n=19) received prefrontal transcranial direct current stimulation (tDCS) at one of two different time points during a vigilance task (early or late). The impact of tDCS was examined using measures of behavior, hemispheric blood flow velocity, and regional blood oxygenation relative to sham stimulation. In the sham condition greater time-on-task was accompanied by fewer target detections and slower reaction times, indicating a vigilance decrement, and decreased blood flow velocity. tDCS significantly altered baseline task-induced physiologic and behavioral changes, dependent on the time of stimulation administration and electrode configuration (determining polarity of stimulation). Compared to the sham condition, with more time-on-task blood flow velocity decreased less and cerebral oxygenation increased more in the tDCS condition. Behavioral measures showed a significant improvement in target detection performance with tDCS compared to the sham stimulation. Signal detection analysis revealed a significant change in operator discriminability and response bias with increased time-on-task, as well as interactions between time of stimulation administration and electrode configuration. Current density modeling of tDCS showed high densities in the medial prefrontal cortex and anterior cingulate cortex. These findings confirm that cerebral hemodynamic measures provide an index of resource utilization and point to the central role of the frontal cortex in vigilance. Further, they suggest that modulation of the frontal cortices—and connected structures— influences the availability of vigilance resources. These findings indicate that tDCS may be well-suited to mitigate performance degradation in work settings requiring sustained attention or as a possible treatment for neurological or psychiatric disorders involving sustained attention.

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Introduction

Background

Vigilance, or sustained attention, denotes the ability to sustain attention to a task for a period of time in order to detect and respond to infrequent critical events (Davies and Parasuraman, 1982; Parasuraman, 1998; Warm et al., 2008). A typical finding in vigilance tasks is the vigilance decrement, which refers to the decline in target detection rate or speed of response over time on task (Mackworth, 1948).

Two theories of the vigilance decrement predominate: the arousal theory and the resource theory. Broadly speaking, according to the former theory, vigilance decreases as an individual’s physiological arousal declines over time (Frankmann and Adams, 1962; Parasuraman, 1985). Classic arousal theory refers to a state of cortical arousal or energy. As such, the ability of stimulants (e.g., caffeine, epinephrine) and inhibitory drugs (e.g., hyosine, chlorpromazine) to alter vigilance state (Prokopova), and the influence of environmental stimuli (e.g., music) on overall levels of vigilance performance (Wolfe and Noguchi, 2009), lends support to arousal theory. However, the arousal theory has not consistently been able to account for the vigilance decrement. For example, physiological signs of reduced arousal with time on task occur whether or not a vigilance decrement occurs, suggesting that the two are not causally linked (Parasuraman, 1985). Furthermore, the theory argues that vigilance tasks are underarousing, which fails to account for the well-documented high stress and mental workload levels associated with vigilance performance (Warm et al., 1996, 2008). The resource theory assumes that cognitive processing relies on a limited pool of resources that, once depleted, lead to performance decrements (Kahneman, 1973; Matthews et al., 2000; Wickens, 1984). Therefore, performance decrements occur because the individual expends resources for maintaining attention at a rate faster than they can be replenished (Parasuraman et al., 1987). Predictions made by the resource theory are consistent with empirical findings related to tests of taxonomies of vigilance (Warm and Dember, 1987), mental workload (Warm et al., 1996), and stress (Matthews et al., 2000). Recent studies have provided independent support for the resource theory by using cerebral hemodynamics as an index of resources (for a review, see Warm and Parasuraman, 2007). It is worth noting that more recent conceptions of sustained attention models have elucidated subtypes of arousal and energy (e.g., Berman and Weinberger, 1990; Deutsch et al., 1988), in other sensory modalities (Warm et al., 1976, 1980), and corroborated with studies in split-brain patients showing more effective performance with right compared to left hemisphere signals (Dimond, 1979a, 1979b).

Interestingly, in frontal lobe patients the most common cognitive disorders result from abnormalities of attention (Fuster, 2009; Wilkins et al., 1987). Frontal lesion patients demonstrate reduced neurophysiologic responses to stimuli, with prefrontal damage (Brodman’s areas 9 and 46) producing impairment in sustained and phasic attention abilities (Stuss and Benson, 1986; Swick and Knight, 1998), as well as more complex cognitive processing (e.g., Nasman and Dorio, 1993). Additionally, Rueckert and Graffman (1996) showed that right frontal lesion patients had longer reaction times and missed more targets in the Continuous Performance Test (CPT), even compared to patients with left and bilateral frontal lesions. Their study was also the first to demonstrate that as the duration of sustained attention increases, the right frontal region becomes increasingly important. Further, attention deficit hyperactivity disorder (ADHD) is typically associated with frontal lobe dysfunction, especially in children. Shue and Douglas (1992) showed differences in children with ADHD versus controls on tasks involving frontal lobe function but not on tasks involving temporal lobe function.

Both lesion and neuroimaging studies have many limitations that are well documented (e.g., Fuster, 2009; Jarrard, 1993). For reasons such as these, lesion studies in humans cannot conclusively demonstrate that the neurons within a specific area are themselves critical to the computational support of an impaired cognitive process, and neuroimaging alone can only be described as an observational, correlational method (Sarter et al., 1996). Further, studies demonstrating brain region changes during vigilance often fail to link the system(s) identified to performance efficiency (Parasuraman et al., 1998). Neuroimaging evidence combined with active neuromodulatory data can yield a stronger level of inference, creating a much more compelling case for the causal role of a brain region for cognitive performance.

Study goals

Although typically used to address neurological disorders such as Parkinson’s disease, major depressive disorder, schizophrenia, stroke, dementia, chronic pain, or explore basic science questions regarding cognitive function, there is a rapidly growing body of literature suggesting that noninvasive brain stimulation techniques such as transcranial magnetic stimulation (TMS) and transcranial direct current stimulation (tDCS) may enhance specific cognitive skills in healthy, normal people. Studies using TMS and tDCS have provided evidence of cognitive performance enhancement in skills ranging from simple picture naming (Mottaghy et al., 2006), phonological memory (Kirschen et al., 2006), working memory (Luber et al., 2008), and verbal fluency (Wassermann and Grafman, 2005), to more complex tasks such as threat detection and recognition (Clark et al., 2012), improved implicit learning (Kincses et al., 2004), and analogical reasoning (Borojjerdi et al., 2001). While both techniques have produced promising results, the underlying technologies are very different. In TMS, a magnetic coil is placed near the subject’s
sculpt and electricity is passed through the coil in brief pulses. This creates a changing magnetic field perpendicular to the human subject's head, which passes unimpeded through the scalp and skull and into the underlying targeted cortical tissue (Wagner, Valero-Cabre, and Pascual-Leone, 2007). This magnetic field induces current (flowing in the opposite direction of the current flow in the coil) in the underlying neural tissue strong enough to raise neuronal membrane potential and force action potentials (Wassermann et al., 2008). Alternatively, tDCS uses a mild direct electrical current passed between electrodes on the scalp to modify neuronal membrane resting potential in a polarity dependent manner, elevating or lowering neuron excitability in a region (Paulus, 2004; Priori, 2003). For a detailed description of these technologies, design, physics, and principles of activation, see Wagner et al. (2007).

Transcranial direct current stimulation (tDCS) is a neuromodulatory technique that applies a small current (typically 1 to 2 mA) to the scalp and is considered safe for periods up to 30 min (Bikson et al., 2009). This noninvasive method, which alters spontaneous neuronal firing among other things, has been described as inducing a temporary “LTP-like” or “LTD-like” plasticity state, depending on the electrode being used (Stagg and Nitsche, 2011). By using tDCS, it is possible to “up-modulate” or “down-modulate” particular brain areas of interest.

In the current study we applied tDCS over the prefrontal cortices during a vigilance task to determine whether modulation of these areas would affect performance and cerebral hemodynamics. We further used nonparametric signal detection theory metrics to examine whether any performance changes were due to changes in perceptual sensitivity (A'), response bias (B'), or both. We hypothesized that active modulation of the prefrontal cortex would reduce vigilance decrement in a time dependent manner. If applied early in the task, tDCS should serve to reduce the extent of the decrement. If applied late in the task, after vigilance decrement has set in, tDCS should restore performance to early task levels. Finally, we hypothesized that such tDCS effects would occur primarily for sensitivity than for response bias.

Methods

Ethics statement

All participants provided informed consent to take part in this study, which was approved by the Air Force Research Laboratory Institutional Review Board.

Participants

A total of 25 military personnel (18 male, 7 female) volunteered to participate in the experiment. Volunteers were excluded if there was any significant lifetime history of mental illness, head trauma, neurological illness, high blood pressure, or drug dependence other than nicotine. They were also excluded if they were pregnant or planning to become pregnant during the study period, had self-reported uncorrectable eye deficiencies (such as colorblindness), or motor deficiencies, as well as if they reported taking prescription or over-the-counter medications which could affect cognitive ability. Of the 25 volunteers, 19 qualified to participate in the study and were divided into two subject groups: “early stimulation” (n = 10) and “late stimulation” (n = 9). The “early” group received stimulation 10 min after the start of the 40-min vigilance task for 10 min, while the “late” group received stimulation 30 min following the start of the 40-min vigilance task for 10 min.

Vigilance task

The vigilance task used in this experiment was a simulated air traffic controller task (adapted from Funke et al., 2010). Three concentric circles divided into four quadrants were shown on a computer display. A static aircraft symbol appeared within each quadrant. In the “safe path” condition, the aircraft were all oriented in same direction: either clockwise around the circle or counterclockwise. The participants were instructed to detect when one aircraft was oriented in the opposite direction of the other three, indicating a collision was imminent. This condition was referred to as the “critical signal”. Participants indicated if they had detected the critical signal by depressing the spacebar on a standard computer keyboard. The “safe path” stimuli did not require a response. A stimulus was presented randomly for 1 s with a one second inter-stimulus interval. The randomization schedule was confined to present approximately 30 critical targets every 10 min.

Signal detection parameters

Signal detection theory provides a framework to measure performance, relating “choice behavior to a psychological decision space” (Macmillan and Creelman, 2009). The current study examined subjects’ abilities to discriminate between signals (stimuli) and noise (no stimuli). Parameters such as hit rate (probability of a subject responding yes on signal trials) and false-alarm rate (probability of responding yes on noise trials) can be calculated and used to yield a subject’s sensitivity (d' or A') and response bias (β or B'). Because the parametric measures of sensitivity (d') and bias (β) require assumptions of normal signal and noise distributions, as well as similar standard deviations with each distribution, which are particularly suspect in yes/no type tasks such as the one employed in this study (Swets, 1986), we chose to utilize nonparametric measures. Described by Pollack and Norman (1964), perceptual sensitivity (A') was calculated using the method provided by Snodgrass and Corwin (1988), as was response bias using Grier's (1971) B" (for complete equations, see Stanislaw and Todorov, 1999).

Transcranial direct current stimulation

The MagStim DC stimulator (Magstim Company Limited; Whitland, UK) was used to provide tDCS stimulation. Current was delivered at 1 mA for 10 min at either 10 min or 30 min after the start of the vigilance task. The battery-powered tDCS device is controlled with a microprocessor to ensure constant current. For safety, multistage monitoring of the output current is included with the device. Two 3 cm × 5 cm (35 cm²) conductive rubber electrodes inside a sponge soaked with physiologic saline were used for current delivery. In the “anodal” stimulation condition, the anode was placed over the left dorsolateral prefrontal cortex (dlPFC) (electrode center over F4 on the 10–20 system), while the cathode was placed near the right dlPFC position (electrode center over F3 on the 10–20 system), while the cathode was placed near the right dlPFC position (electrode center over F4 on the 10–20 system). The electrodes were reversed for the “cathodal” treatment condition. Sham stimulation included a 15 s ramp up to 1 mA, followed by a 30 s plateau at that level. The current was then reduced back to zero over 15 s. Half of the participants received sham stimulation via the “anodal” electrode position, while the other half received sham through the “cathodal” electrode position.

Procedures

Volunteers received a verbal briefing that described the vigilance task followed by two 5 min practice sessions. They were then asked to complete the vigilance task for 40 min. Participants wore earplugs to reduce ambient sounds, and a screen was placed in between the investigator and the participant to eliminate distractions. While performing the vigilance task, a Sonara/tek transcranial Doppler (TCD) (Conshohocken, PA) was used to record the participant’s blood flow velocities in both the left and right middle cerebral arteries (MCA), which is typically the standard Doppler placement for
monitoring during vigilance tasks (e.g., Warm and Parasuraman, 2007) as they supply 80% of the blood flow within each hemisphere (Netter, 1989; Toole, 1984). Additionally, an INVOS 4100 cerebral oximeter (Somanetics; Troy, MI) was used to collect regional oxygen saturation (rSO2) values. The oximetry sensors were placed bilaterally over the forehead to record rSO2 within the frontal cortex. Cerebral blood flow velocities and performance data were used as an additional screening technique. Because this experiment was designed to examine the interaction between the vigilance decrement and tDCS, participants without changes in blood flow velocity and performance over the vigil (data assessed visually) were not asked to return for further data collection. If, however, performance and blood flow velocity declined over the course of the 40 min vigilance task, the participants were invited to complete the remaining procedures.

Participants returned to the laboratory three more times, each visit no less than 2 days apart. Each participant received all three tDCS conditions (within variable: anodal, cathodal, sham) in a randomized order, with each occurring on a different day. They were also randomly assigned to one of two groups (between variable): “early” received tDCS 10 min after the start of the task for a duration of 10 min; and “late” received tDCS 30 min following the start of the task for 10 min (see Fig. 1).

Prior to performing the task, participants were asked to fill out a mood questionnaire as described by Clark et al. (2012). Participants were then given earplugs and instrumented with the TCD, oximeter sensors, and tDCS electrodes. They then completed the 40 min vigilance task while receiving stimulation at the appropriate time point. Once completed, the participants again filled out the mood questionnaire and their scores were compared. Participants were asked to remain in the laboratory if a change in score of 3 or more was detected on any question. After 15 min, they were asked to fill out the mood questionnaire again to ensure there was no lingering aftereffects of the stimulation.

Data analysis

Trials were divided into four 10 min blocks. Data were baselined to the first 10 min block of each trial. Measures were then compared as a percentage change from baseline. Because the TCD signal is sensitive to small movements from the ultrasound emitter position, the signal quality in 5 of the data files was too poor for inclusion in the final analyses. Likewise, fragility in the oximeter sensors and noise created by saline from the tDCS electrodes resulted in the partial or entire loss of 18 data files (out of 114). The mixed procedure in SAS was used to perform mixed model analyses of variance, and the estimation method used was restricted/residual maximum likelihood (REML). This method was used instead of least squares to better deal with missing data (Little and Rubin, 2002). The REML method can generate post-hoc analyses involving least squares means (LSMeans) that are unable to be obtained under certain patterns of missing data using least squares. Post-hoc paired comparisons used LSMeans. The significance level was set at p<0.05.

Current density modeling

The current from the tDCS was modeled using the Brain Online Stimulation Analysis Imager (BONSAI) (http://neuraleng.com/bonsai/). Though this tool is still in beta testing and not verified, its underlying methodology has been used and published by the development group elsewhere (e.g., Dasilva et al., 2012; Turkeltaub et al., 2011). We present it here simply as a visualization tool to better understand where current densities may have collected given our stimulation parameters.

Results

Performance

For percentage of hits, there was a significant effect of type of stimulation (anodal, cathodal, sham), F(2,28.8) = 8.8, p = 0.00; a significant interaction between group (early/late stimulation) and time (20, 30, 40 min), F(2,29.2) = 3.86, p = 0.03; and, a significant interaction between type of stimulation and time, F(4,31.3) = 2.74, p = 0.04. As shown in Fig. 2, overall hit rate was greater in tDCS relative to the sham condition. Contrasts from the early stimulation group showed that hits in the anodal group were significantly higher than for both cathodal and sham conditions for the 20 min block (p = 0.01). Furthermore, in the sham condition hit rate continued to decrease compared to both anodal and cathodal conditions in the 30 min block (p = 0.00) and 40 min block (p = 0.00). In the late stimulation group, contrasts were significant for a difference in sham at the 20 min block (p = 0.00) and anodal at the 30 min block (p = 0.03). The percentage change of false alarms (response to neutral targets) had a significant interaction between time of stimulation (early/late) and type of stimulation (anodal, cathodal, sham), F(2,25.3) = 3.59, p = 0.02 (Fig. 4). Contrasts indicate late anodal stimulation caused a significant reduction in false alarm rate between the 30 and 40 min blocks (p = 0.00). To summarize the hit and false alarm data analyses, polarity of the stimulation appeared to have a significant, positive effect on hit performance. This was most evident in the early anodal stimulation group. Further, late anodal stimulation led to decreased false alarms. Hit rate in the late stimulation group was found to be
significantly different from both cathodal and anodal stimulation at 20 min, which was before any stimulation had been administered. The reason for this finding is unknown and might be attributed to a sort of stimulation expectancy; however, stimulation order was not found to be significant, the finding was not replicated in other behavioral measures, and early/late subject grouping was a between-subjects variable, meaning subjects in the late group never experienced stimulation at the 10 min point.

Reaction time was significantly affected by time on task $F_{1,630} = 5.15$, $p = 0.00$ (Fig. 3). Contrasts for each block showed significantly slower reaction times for each progressive block of 20 min ($p = 0.00$), 30 min ($p = 0.00$), and 40 min ($p = 0.00$). These findings demonstrated time on task had a significant effect on reaction time, increasing the time to respond for each subsequent block. No significant effect of tDCS was observed.

Signal detection analysis revealed significant effects for $A'$ (operator sensitivity) and $B'$ (operator response bias) via ANOVAs (Fig. 5). Sensitivity decreased significantly based on time (20, 30, 40 min), $F_{1,5.125.8} = 4.01$, $p = 0.01$, and interacted with time and group (early, late stimulation), $F_{1,5.5.125.8} = 4.91$, $p = 0.00$, and time and stimulation type (anodal, cathodal, sham), $F_{1,6.96} = 2.41$, $p = 0.03$. Operator bias showed a significant interaction between time and stimulation type, $F_{1,6.96} = 2.36$, $p = 0.03$. Signal detection parameters for operator sensitivity and response bias showed significant changes for time and stimulation, with time decreasing discriminability and stimulation causing changes in response bias at the different administration points.

**Physiology**

Blood flow velocity was significantly affected by time (20, 30, 40 min), $F_{1,2,65.3} = 19.02$, $p = 0.00$ (Fig. 6). There was also a significant 3-way interaction between group (early/late stimulation), side (left, right middle cerebral artery), and time, $F_{1,2,63} = 4.00$, $p = 0.02$. Contrasts revealed a significant decrease in blood flow velocity for the left MCA in the 30 min block for the late stimulation group ($p = 0.01$); significant decrease for the right MCA in the 30 and 40 min blocks for the early sham stimulation group ($p = 0.00$ for both); and significant decrease in the right MCA for the late sham stimulation group in the 20 ($p = 0.01$), 30 ($p = 0.01$), and 40 min ($p = 0.04$) blocks. There was also a significant decrease in the right MCA for the late cathodal stimulation group in the 30 min block ($p = 0.00$).

An ANOVA for cerebral oxygenation showed a significant interaction between group (early/late stimulation) and time (20, 30, 40 min), $F_{1,2,66.8} = 3.70$, $p = 0.03$ (Fig. 7). Contrasts demonstrated a significant increase for the left forehead in the early anodal stimulation group in the 20 ($p = 0.02$), 30 ($p = 0.00$), and 40 min ($p = 0.02$) blocks. A significant increase was also observed for the left forehead in the late anodal stimulation group in the 40 min block ($p = 0.02$). For the right forehead, there was a significant increase in rSO2 observed in the early anodal stimulation group in the 20 min block ($p = 0.01$). To summarize the physiologic measurement analyses, time on task significantly decreased blood flow velocity. This decrease was mostly pronounced in the right MCA in the non-stimulation (sham) condition. Cerebral oxygenation significantly increased, mostly in response to anodal stimulation.

Overall, significant effects between sham and active stimulation were observed in the physiologic measures, though the effects were complex, depending on type of stimulation (anodal/cathodal), time of stimulation (early/late), and hemisphere being measured (left/right). Generally, anodal stimulation (meaning cathodal stimulation was over the right hemisphere) led to decreased hemispheric blood flow velocity change and increased cerebral oxygen saturation. Blood flow velocity measures in the right Doppler appeared to be more responsive to tDCS than left Doppler.

**Discussion**

This study aimed to investigate the role of the prefrontal cortices during sustained attention, and whether prefrontal stimulation using tDCS can diminish the vigilance decrement. Unlike previous studies of vigilance that have used either frontal lesion or neuroimaging methods, our study directly manipulated cortical functioning in the prefrontal cortices. Further, we attempted to use tDCS not simply as a basic science exploratory technique but also as a possible method for operational performance intervention. Our vigilance task reproduced behavioral and physiologic effects typically observed in similar experiments (Helton et al., 2007; Warm and Parasuraman, 2007), with decreased hit percentages, increased reaction times, and decreased blood flow velocity in the MCA. We also found that 1 mA compared to sham tDCS had significant effects on both performance and cerebral hemodynamics. These effects were most prominent in the anodal stimulation type (anodal electrode placed over the left dlPFC), but also visible in many dependent variables for cathodal stimulation. Further, changes were observed in operator characteristics using nonparametric signal detection theory parameters (Stanislaw and Todorov, 1998). Our results fit well within the resource theory

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of vigilance and suggest that resource utilization may be augmented via exogenous stimulation. We note, however, that the current methodology cannot determine if tDCS affected the actual resources being utilized or aided in some aspect of their utilization, such as modulating a subcomponent of arousal-based attentional enhancement (e.g., energetic arousal, task engagement; Matthews et al., 2010).

Classic arousal theory cannot fully explain our current results for a number of reasons. The modulation of prefrontal cortices leading to improved performance was not accompanied simply by increases in false alarm rate. Arousal-amplifying approaches (e.g., pharmacological) typically lead to significant changes in operator characteristics, particularly operator bias (β, or B in our study) (Posner, 1978). A recent study using a complex target detection task demonstrated that tDCS of the prefrontal cortices led to significant effects on perceptual sensitivity (d’, or A for this study) but not on response bias (β, or B) (Falcone et al., 2012). We argue that tDCS modulation of prefrontal cortices restored resource or resource-constituents necessary for performance, though we did not assess arousal level per se and cannot rule out arousal-mediated effects. The enhancement was most notable with anodal stimulation over the left dlPFC, which supports the resource interpretation if one assumes that nonspecific arousal would not be influenced by the specific polarity configuration.

Further, there is no literature that we are aware of which suggests that tDCS preferentially affects arousal systems. Similarly, many studies demonstrating tDCS effects also reject non-specific, arousal-driven mechanisms as a possibility (Antal et al., 2004; Boros et al., 2008; Flöel et al., 2008; Nitsche et al., 2007).

Differences between stimulation polarities may possibly be explained through modulation of discrimination ability. Executive control of vigilance is often linked to the right hemisphere, as is global discrimination of stimuli. Local discrimination of stimuli, however, has been found to be left hemisphere dominant (Lux et al., 2004; Yamaguchi et al., 2000). Based on Kinsbourne’s (1982) theory of hemispheric interference (i.e., cognitive processes in connected anatomical regions cause interference with each other), Helton et al. (2009) found improved vigilance performance when processing load was shared across hemispheres versus combined in a single hemisphere. The tDCS in our experiment could be considered a type of exogenously-applied but endogenously-induced interference, possibly encouraging or hindering cognitive processing depending on the processing strategy (global/local) used by the subject. Because the task used has been shown to be lateralized to the right hemisphere with blood flow velocity changes (Funke et al., 2010), this would suggest it is accomplished mostly through global discrimination.

![Fig. 5. Signal detection parameters. Left figure: changes in operator perceptual sensitivity (discriminability). Right figure: changes in operator response bias. Early Group (stimulation at 10–20 min); Late Group (stimulation at 30–40 min).](image)

![Fig. 6. Blood flow velocity percent change from baseline. Early Group (stimulation at 10–20 min); Late Group (stimulation at 30–40 min).](image)
Performance improvement due to anodal stimulation over the left hemisphere could imply enhancement of local discrimination processing but also increased sharing of the cognitive processing load.

Task difficulty, which has been shown to affect the laterality of vigilance processing (Helton et al., 2010), may also help explain differences in tDCS polarity. Helton and colleagues found the easier a vigilance task, the greater activation was in the right hemisphere. Greater cognitive load led to a shift in bilateral activation. Because tDCS alters membrane potential and spontaneous firing rates, it is likely this increase or decrease in “neuronal noise” affects processing in the region. As our task has been shown in the past to be right hemisphere lateralized, suggesting that it is not difficult, and anodal stimulation in the left dlPFC may have led to increased cognitive processing recruitment typically seen in more difficult tasks, again decreasing cognitive processing load in the right hemisphere.

In light of the present results, the dominant role of the right prefrontal cortex in the vigilance decrement and perhaps, more generally, in sustained attention comes into question. Given the electrode montage and the nature of current flow between two electrodes, our stimulation can be thought of as imparting a “push–pull” effect among hemispheres, with comparable current densities in each hemisphere (Bikson et al., 2008, 2009). When the anodal electrode is placed over the left dlPFC, leading to an “LTP-like” state, it is also reasonable to consider that the return electrode near the right dlPFC would be causing a local “LTD-like” state. Consequently, our results must be interpreted not solely as a modulation of a single hemisphere, but as a simultaneous hypo- and hyper-polarization of the stimulated frontal cortices. With anodal stimulation of the left dlPFC, results should perhaps also be interpreted as “cathodal stimulation of the right dlPFC” (e.g., Bikson et al., 2010). This may explain why there were no greater discrepancies between cathodal and anodal stimulation effects. The majority of tDCS effects were seen with the combination of up-modulation (anodal) of the left dlPFC and down-modulation of right dlPFC (cathodal). Posner and Petersen (1990) suggested a right lateralization of the vigilance system due to greater innervation of the right hemisphere by the ascending noradrenergic pathways. Anodal stimulation showed some recovery from the decrement in the late stimulation group, meaning down-modulation of the right dlPFC during reduced hemispheric blood flow was beneficial without a corresponding increase in blood flow.

Fig. 7. Cerebral oxygenation percent change from baseline. Early Group (stimulation at 10–20 min); Late Group (stimulation at 30–40 min).

Fig. 8. Current density modeling with right and left dlPFC electrode montage at 1 mA. Upper part of figure shows current density modeling, with darker areas suggesting greater current density. Lower part of figure shows slice location for orientation.
This is also the first study to demonstrate hemodynamic blood flow velocity change in response to tDCS of the dlPFC. Further, our results support previous work (Merzagora et al., 2010), showing increased regional oxygenation levels near the anodal electrode.

As shown in Fig. 8, the current density from the electrode montage used may have affected regions well beyond the targeted prefrontal cortices. Of particular interest are possible influences from the cingulate cortex. Structurally, the dlPFC and anterior cingulate cortex (ACC) are strongly interconnected (Barbas, 1992), making observations of high current density in this region not unexpected due to likely greater conductivity of white matter tracts (e.g., Pardo et al., 1991; Paus, 2001), so we cannot attribute our results solely to modulation of dlPFC.

Conclusions

Many everyday tasks require humans to observe and detect infrequent and unpredictable signals over extended periods of time (Warm et al., 2008). Further, technological systems are becoming increasingly automated, which is transforming the roles of many workers from traditional active controllers of systems to supervisory control positions. Supervisory control positions require workers to monitor the function of complex systems and to only intervene if there is a potential problem or malfunction (Sheridan, 1970, 1980). The shift from active control to supervisory control means that vigilance is becoming an increasingly vital component of human operator performance in a wide array of work environments. Consequently, it is becoming even more important to attain a deeper understanding of vigilance mechanisms and to develop technology for augmenting vigilance. The current findings show promise for the development of tDCS as an intervention to counteract vigilance decrements. While the current study presents a promising technique for exploring, and possibly alleviating, the vigilance decrement, more research must be performed on the repeated use of tDCS to establish safety guidelines before such technologies can be employed in the workplace. Current multisession studies often conclude after five consecutive days of tDCS administration (e.g., Alonzo et al., 2012; Gámez et al., 2012) without negative effects; however, the consequences of more chronic repeated tDCS use (i.e., weeks, months) are not known.

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