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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., hyoscine, 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 suggest a more complex interaction between arousal and resource systems (cf. Helton and Warm, 2008; Helton et al., 2009b; Manly et al., 1999; Matthews et al., 2010; Robertson et al., 1997).

Though attentional networks are spread throughout the brain, frontal regions have been heavily implicated in vigilance tasks (see Parasuraman et al., 1998). A large number of PET and fMRI vigilance studies suggest lateralized frontal lobe activation during the performance of a vigilance task, with a concentration of activity in the right prefrontal cortex (Berman and Weinberger, 1990; Buchsbaum et al., 1990; Cohen et al., 1988; Cohen et al., 1992; Coull, Frackowiak, and Frith, 1998; Deutsch et al., 1988; Lewin et al., 1996; Pardo et al., 1991; Reivich and Gur, 1985). These effects have also been seen with other techniques such as regional cerebral blood flow (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 (Brodmann'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 Grafman (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, correlative 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 (Boroojerdi et al., 2001). While both techniques have produced promising results, the underling technologies are very different. In TMS, a magnetic coil is placed near the subject's