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At the Forefront of HF/E

Using Noninvasive Brain Stimulation to Accelerate Learning and Enhance Human Performance

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Objective: The authors evaluate the effectiveness of noninvasive brain stimulation, in particular, transcranial direct current stimulation (tDCS), for accelerating learning and enhancing human performance on complex tasks.

Background: Developing expertise in complex tasks typically requires extended training and practice. Neuroergonomics research has suggested new methods that can accelerate learning and boost human performance. TDCS is one such method. It involves the application of a weak DC current to the scalp and has the potential to modulate brain networks underlying the performance of a perceptual, cognitive, or motor task.

Method: Examples of tDCS studies of declarative and procedural learning are discussed. This mini-review focuses on studies employing complex simulations representative of surveillance and security operations, intelligence analysis, and procedural learning in complex monitoring.

Results: The evidence supports the view that tDCS can accelerate learning and enhance performance in a range of complex cognitive tasks. Initial findings also suggest that such benefits can be retained over time, but additional research is needed on training schedules and transfer of training.

Conclusion: Noninvasive brain stimulation can accelerate skill acquisition in complex tasks and may provide an alternative or addition to other training methods.

Keywords: noninvasive brain stimulation, neuroergonomics, cognitive neuroscience, learning, cognition, memory (short-term, long-term, working memory)

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INTRODUCTION

Developing expertise in complex work-related tasks typically requires extensive practice, 10,000 hr according to one estimate (Ericsson, Krampe, & Tesch-Romer, 1993). Although many training techniques have been developed and evaluated in human factors and related disciplines, many are slow, costly, and based on theories that are decades old. Are there newer theory-based methods for accelerating skill acquisition?

Neuroergonomic investigations of modulation of human brain function may offer an answer, by providing empirical findings that constrain and refine theories of human performance and new methods to study humans at work (Parasuraman, 2011; Parasuraman & Wilson, 2008; Posner, 2012). One such promising new method is noninvasive brain stimulation.

Skill acquisition is known to involve both declarative (“knowing that”) and nondeclarative or procedural (“knowing how”) components of learning and memory, each having different functional characteristics and distinct neural bases (Squire, 2004). In this mini-review, we provide examples of the use of brain stimulation to accelerate both these forms of learning in complex work-related tasks.

Theory: Brain Plasticity

The neural mechanisms of human learning are becoming increasingly understood, with much of the impetus coming from new findings regarding *plasticity*, the ability of the human brain to change its structure and function with experience. The brain is known to undergo dynamic changes from infancy to late adolescence. What is less well appreciated is that the *adult* human brain retains a capacity for plasticity (Huttenlocher, 2002), even well into old age (Greenwood & Parasuraman, 2012).

Consider teaching people a novel skill, such as juggling a three-ball cascade. Using MRI scans of naive individuals before and after 3 months spent practicing juggling, Draganski et al. (2004) found that participants showed increases in cortical gray matter in brain regions important in perceptual-motor coordination. After another 3 months without juggling, these cortical regions reverted, although not completely, to their original size. The integrity of the white-matter connections underlying task-related cortical regions also increases with practice, not only in perceptual-motor tasks, like juggling (Scholz, Klein, Behrens, & Johansen-Berg, 2009), but also in cognitive tasks, such as working memory (Takeuchi et al., 2010).

Noninvasive brain stimulation can complement such motor and cognitive training as a means to enhance brain plasticity. In particular, brain stimulation *in conjunction with* training may accelerate skill acquisition by boosting natural plasticity processes involved in memory formation, such as long-term potentiation (Raineri et al., 2012). Without exogenous stimulation, training-related neural changes emerge only after several weeks or months.

Noninvasive Brain Stimulation Methods

Many noninvasive brain stimulation techniques for enhancing brain function and performance exist, including transcranial magnetic stimulation (TMS) and transcranial direct current simulation (tDCS) (Clark & Parasuraman, 2014). TMS involves use of a magnetic coil positioned over the participant's scalp over a brain region of interest. Electric current is passed through the coil for brief periods, creating a changing magnetic field that passes through the skull and induces current flow in the underlying cortical tissue sufficient to alter neural firing (Walsh & Pascual-Leone 2005). TDCS involves a small DC electric current (1 to 2 mA) with electrodes attached to the scalp. A positive polarity (anode) is typically used to stimulate neuronal function and enhance performance. Conversely, a negative polarity (cathode) is used to inhibit neuronal activity. Application of tDCS is safe for experimental use in healthy participants for up to 30 min of stimulation (Bikson, Datta, & Elwassif, 2009).

TMS and tDCS can be independently used to modulate neuronal function. They can also be used in conjunction when, for example, activity in one brain region is reduced (e.g., with TMS) while boosting brain activity elsewhere (e.g., with tDCS) (Galea & Celnik, 2009). TMS has superior spatial resolution to tDCS in targeting specific brain regions but is costly, is not portable, and is suitable only for seated participants. In contrast, tDCS is a low-cost portable technique that can be used in mobile participants. In this paper, we focus on tDCS, given the recent prevalence of studies using this technique.

EFFECTS OF TDCS ON COGNITION

The mechanism by which tDCS influences brain function and cognition is not precisely known and is a topic of intense research. Initially, it was thought that application of weak DC current increases the resting neuronal membrane potential and thus lowers the threshold for firing of neurons (Bindman, Lippold, & Redfearn, 1964), but subsequent work suggests that other mechanisms are probably involved, such as dynamic modulation of synaptic efficacy (Rahman et al., 2013).

For tDCS to be effective, it must be paired with a task that engages the trainee's brain regions controlling a specific cognitive function (Clark et al., 2012). TDCS is not like a drug or a nutrient that can be passively taken in an attempt to boost brain activity and cognition, since it is believed the current alone is in many cases insufficient to directly modulate neuronal action potentials in a brain region if it is not actively involved in task performance. In addition, the placement and polarity of tDCS electrodes is critical for obtaining effects on performance. The anode is typically placed on the scalp overlying the brain region to be stimulated, and the cathode is placed either on another scalp area or on the body, such as the shoulder. Sometimes the cathode is placed over a scalp location to depress brain functions competing with the cognitive skill that is the focus of enhancement.

Figure 1 shows a framework for using tDCS in training studies. Electrode placement sites are determined in one (or both) of two ways. First, neuroimaging evidence on the brain networks that are involved in a particular cognitive task can be used to guide the electrode sites for

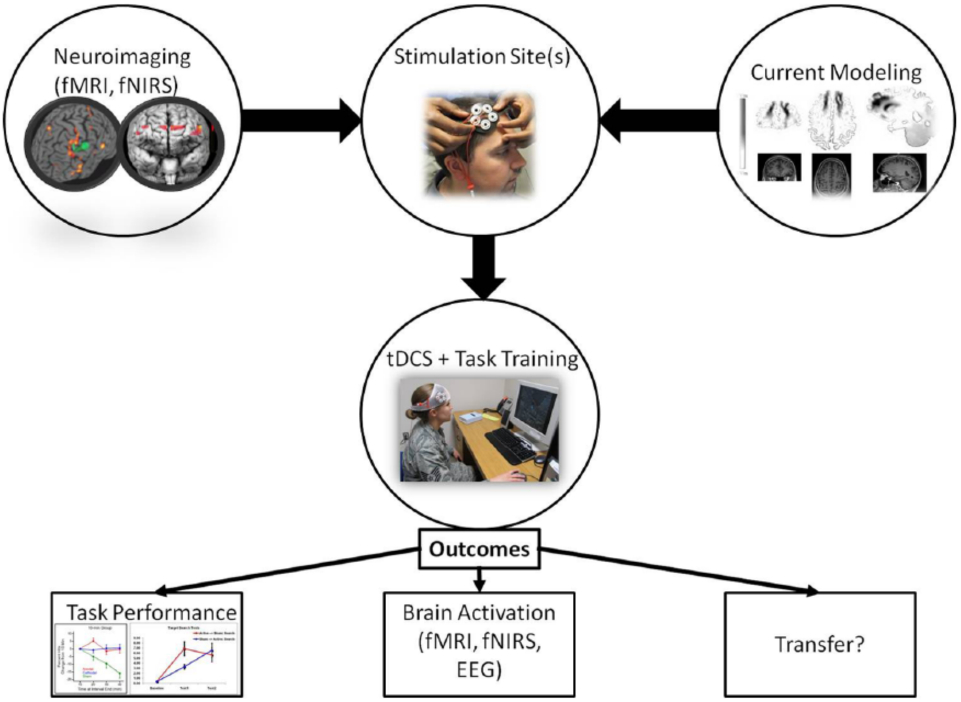

Figure 1. A framework for conducting noninvasive brain stimulation studies of training. TDCS = transcranial direct current stimulation; fMRI = functional magnetic resonance imaging; fNIRS: functional near infrared spectroscopy; EEG = electroencephalography. The question mark in the lower-right box (transfer) reflects the fact that whereas there is good evidence on the task performance and brain activation outcomes of tDCS training, to date, there are few studies on the third outcome, transfer.

stimulation. Second, modeling of the current flow into the brain can be used to estimate the electrical field intensity associated with different electrode sites and currents. This model in turn can be used to optimize the electrode location(s) that lead to maximum current flow in a region of interest (Datta et al., 2009). TDCS applied to the resulting electrode site, in conjunction with training on a cognitive task, can yield several potential outcomes, including (a) enhanced performance, (b) altered neural activity as reflected in neuroimaging measures, and (c) transfer to different tasks in the same domain of cognition.

Many studies have found that stimulation of different brain regions with tDCS can enhance performance of basic cognitive tasks that recruit the corresponding brain regions. For example, neuroimaging studies have implicated the dorsolateral prefrontal cortex (DLPFC) in working-memory tasks; applying tDCS to a scalp location over this region accordingly enhances working memory (Fregni et al., 2005). TDCS has also been found to enhance procedural learning, in the form of motor skill acquisition (Galea & Celnik, 2009). For reviews of the effects of tDCS on cognition, see Coffman, Clark, and Parasuraman (2014) and Jacobson et al. (2011). For reviews of the effects of TMS on cognition, see Walsh and Pascal-Leone (2005) and McKinley, Nelson, Bridges, and Walters (2012). Here we provide examples of the effects of tDCS on more complex tasks representative of work settings.

EFFECTS OF TDCS ON COMPLEX COGNITIVE WORK TASKS

Surveillance and Security Operations

Accurate and timely detection of obscured or concealed objects, or the actions and movements of other people, is a critical need in many civilian and military surveillance environments. For example, cameras on uninhabited vehicles (Cooke, Pringle, Pedersen, & Connor, 2006) and closed-circuit television monitors (Dadashi, Stedmon, & Pridmore, 2013) are increasingly being used to provide video images to remotely located operators for identification of potential threats. Skill in such threat detection tasks typically develops only after extensive training. Furthermore, exponential growth in the number of images or full-motion videos that must be processed has led to an information overload problem so that even trained observers make errors and may require refresher training (Van Coillee et al., 2014).

Recent research suggests that tDCS can accelerate skill acquisition in such threat detection tasks (Clark et al., 2012; Coffman et al., 2012; Falcone, Coffman, Clark, & Parasuraman, 2012). These studies involved use of a complex task requiring participants to watch videos of naturalistic scenes containing movements of soldiers and civilians (MacMillan, Alexander, Weil, Littleton, & Roberts, 2005). Still images were extracted from the videos and manipulated so that half contained threats, defined as concealed objects (e.g., bombs), people engaging in threatening activity (e.g., snipers), and so on. Nonthreats showed the same scene but without the critical threat-related feature. Participants were told only that they were to determine whether or not there was a threat present, without specific details—a discovery-learning paradigm. Figure 2 (top) shows an example threat involving a civilian with a concealed weapon behind his back (in his belt), with the corresponding nonthreat shown in Figure 2 (bottom).

A functional MRI (fMRI) study was first conducted to determine optimal sites for application of tDCS (Clark et al., 2012). The results indicated that the right inferior frontal gyrus was the major locus of a distributed brain network that mediated acquisition of the threat detection task and so was chosen as the optimal stimulation site. Falcone et al. (2012) examined whether tDCS applied to this location enhanced perceptual sensitivity in threat detection, as opposed to inducing a more liberal response bias due to nonspecific effects on arousal (Broadbent, 1971). If tDCS only lowers response bias so that participants are more likely to respond positively in a detection task, the hit rate will increase, even without a change in the participant's perceptual sensitivity (Green & Swets, 1966). Participants were given four training blocks of 60 trials each and were required to indicate whether a threat was present or absent. After each participant's response, a short feedback video was presented informing him or her of each of four possible outcomes—hit, miss, false alarm, or correct rejection—but consistent with discovery learning, the feedback did not provide specific information as to the identity of the threats. Two test blocks were given before training and were similar to training blocks, except that no feedback was given after each response. Anodal tDCS was applied to the electrode site F10 in the electroencephalography system, over the right sphenoid bone, corresponding to an area overlying the inferior frontal

Figure 2. Examples of images indicating threat (top) and nonthreat (bottom) scenes.

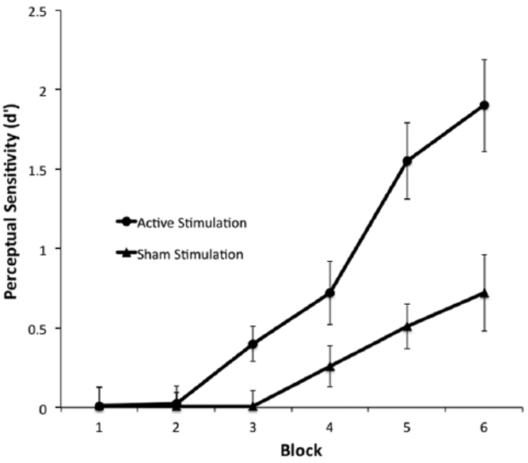

Figure 3. Changes in perceptual sensitivity (*d′*) of threat detection over blocks with active (2 mA transcranial direct current stimulation) or sham stimulation (0.1 mA). The first two blocks were test blocks, followed by four training blocks. Adapted from Falcone, Coffman, Clark, and Parasuraman (2012).

gyrus. The cathode was placed on the contralateral (left) upper arm. Participants were randomly assigned to either active (2 mA current) or sham stimulation (0.1 mA) from the tDCS unit for a total of 30 min during the first two training blocks.

Figure 3 shows the changes with training in the perceptual sensitivity measure *d′* (Green & Swets, 1966). Compared to the 0.1 mA sham stimulation control, 2 mA stimulation increased perceptual sensitivity in detecting targets and accelerated learning. Performance was near chance (*d′* = 0) in both groups at the beginning of training. However, skill acquisition with tDCS was both rapid and extensive: On completion of training, participants in the active stimulation group had more than double the *d′* of the control group. There were no group or training effects on the response bias measure β, indicating that tDCS improved the actual efficiency of threat detection.

An important issue in noninvasive brain stimulation is the extent to which any performance benefits are retained over time. Falcone et al. (2012) provided initial data relevant to this question. They found that threat detection sensitivity remained at a high level immediately after training and, more importantly, 24 hr later. This last finding bodes well for the use of tDCS as a training method with potentially lasting effects.

Intelligence Analysis

Intelligence analysis is an occupation with features in common with surveillance and security. Analysts are tasked with finding targets or regions of interest in vast numbers of still images. The job is difficult and arduous, requiring slow, deliberate visual search. Low-bandwidth communications, noise, or sensors that do not produce sharp images (e.g., radar) can add to the difficulty of the analyst's task. Can tDCS accelerate skill acquisition in such tasks?

McKinley, Weisend, McIntire, Bridges, and Walters (2013) trained image analysts to find and correctly identify ground targets, such as tanks and surface-to-air missile launchers, in synthetic aperture radar (SAR) imagery. Stimulation of the right frontal cortex, using the same anodal F10 scalp location (cathode on the contralateral bicep) as in the previously described surveillance study, significantly improved object recognition learning rates. During the first phase of training, one group was given active tDCS for 30 min; another, sham tDCS (active tDCS for 30 s); and a third group, no tDCS. Participants were then given a second round of training with the stimulation conditions reversed (i.e., the active tDCS group switched to sham tDCS, whereas the sham tDCS group received active tDCS in the second round). Both groups experienced larger increases in target acquisition accuracy when given active tDCS when compared to sham or no stimulation in either Session 1 or 2 (Figure 4). These gains with tDCS may have been caused by a variety of factors, including attention modulation or Hebbian learning (i.e., increased synaptic strength between coactivated neurons).

The image analysis task also included a change detection task in both training sessions. After the target image was complete, one of the targets (randomly assigned) changed in one of four ways: It changed orientation, position, or target type or disappeared completely. Change detection performance was improved only when tDCS was applied in the second session. Thus,

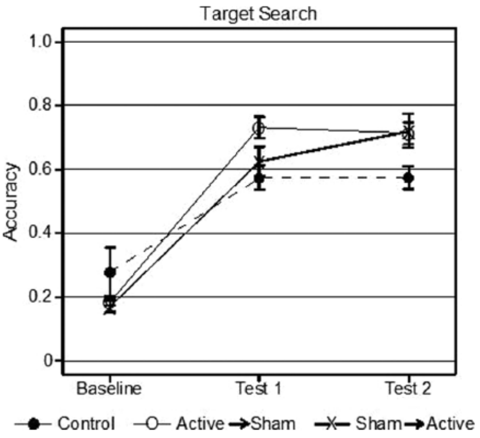

Figure 4. Target search and identification accuracy as measured by the number of correct responses divided by the total number of responses. Adapted from McKinley, Weisend, McIntire, Bridges, and Walters (2013).

tDCS aided in change detection only after the analyst gained some experience with the images and target types. Similarly, Coffman et al. (2012) found that tDCS had a larger effect on threat detection for images that had been viewed previously. These findings may reflect tDCS-induced plasticity changes in the brain networks responsible for object encoding and retrieval.

Procedural Learning in Complex Monitoring

The previous two examples show that tDCS can enhance declarative learning processes contributing to complex skill acquisition. Extensive research suggests that there is a dynamic balance between the declarative and procedural memory systems of the brain (Eichenbaum & Cohen, 2004). Thus, disruption of one memory system may lead to enhancement in the other. In a proof-of-concept study, Galea and Celnik (2009) showed that disruption of the declarative system by TMS-based inhibition of DLPFC directly after motor skill acquisition enhanced procedural memory consolidation and subsequent recall.

McKinley, Nelson, McIntire, Nelson, and Weisend (2012) used cathodal tDCS of DLPFC to examine whether similar effects could be found in performance of a more complex task involving procedural learning. Participants were trained to learn the procedures and rules in “Warship Commander,” a task involving both motor (order of button presses) and cognitive (rule-based procedure) components (St. John, Kobus, & Morrison, 2002). Cathodal tDCS applied over DLPFC directly after training led to superior procedural performance 24 hr after training when compared to anodal tDCS applied over the motor cortex or sham tDCS. Participants receiving tDCS over DLPFC improved their score by more than 60% over those that received sham, although there were no differences in the number of correct or incorrect button presses among the groups. This finding indicated that participants were able to process more targets in the allotted time and thus were faster at performing the procedure.

These findings suggest that inhibition of DLPFC can shift the balance between declarative and procedural memory systems to significantly accelerate procedural learning. To our knowledge, this is the first use of inhibitory tDCS to facilitate new learning. This research supports a theory recently posited by Brem, Fired, Horvath, Robertson, and Pascuale-Leone (2014) that cognitive enhancement may reflect reduced “noise” or interference effects in competing brain networks.

DISCUSSION AND CONCLUSIONS

We have described how tDCS can be used to augment brain plasticity and accelerate learning. The efficacy of tDCS for skill acquisition has been demonstrated in a variety of complex tasks, from threat detection to rule-based learning. Learning involves the interplay of declarative and procedural memory systems. TDCS influences both systems. However, stimulation parameters differ depending on the desired strategy. Either excitation of a functionally relevant brain region or inhibition of competing circuits can be effective in accelerating learning. Furthermore, the beneficial effects of tDCS have been shown to persist at least 24 hr.

Although tDCS shows promise as a training method, important questions remain unanswered. To maximize effects on training, optimal stimulation schedules (i.e., every day, twice a week, etc.) need to be determined. Juvina, Jastrzembski, and McKinley (2013) used a computational modeling approach to predict the optimal tDCS scheduling, but empirical validation is required. Second, at what point in training should tDCS be applied? One study showed that tDCS was more beneficial in the early phases of training (Bullard et al., 2011), whereas another showed benefits at all stages (McKinley et al., 2013). Importantly, these studies involved different learning tasks, so it is possible that the optimal time point for tDCS efficacy is task dependent. Likewise, different electrode placements may be optimal for different stages of learning. Third, how long is the learned information retained, and does this change with repeated doses of tDCS? Initial evidence suggests that tDCS-induced improvements in learning are retained for at least 24 hr (Falcone et al., 2012); however, there is little evidence of exactly how long the new knowledge is retained. Finally, the "gold standard" of any training technique is not only whether it is effective in accelerating learning on a particular task but whether its effects transfer to others tasks within the same cognitive domain (Dahlin, Neely, Larsson, Backman, & Nyberg, 2008; Strenziok et al., 2014). TDCS will ultimately need to be held to this high standard.

Noninvasive brain stimulation is not a panacea, and its effects need to be carefully evaluated. One possibility is that brain stimulation is a "zero-sum" proposition, so that enhancement in one cognitive domain is balanced by decrement in another (Brem et al., 2014). For example, Iuculano and Cohen Kadosh (2013) found that anodal tDCS over posterior parietal cortex improved numerical learning but inhibited automaticity, whereas the reverse was true with stimulation of prefrontal cortex. To date, however, evidence of performance costs of tDCS is limited, and additional research is needed on the effects of tDCS on multiple cognitive tasks.

In addition, as with any cognitive enhancement method, there are ethical issues in the use of noninvasive brain stimulation with healthy adults that need to be carefully examined (Hamilton, Messing, & Chaterjee, 2011). We believe that decisions to use tDCS must be informed by empirical evidence (Parasuraman & Galster, 2013) and cost-benefit analyses (Brem et al., 2014) and not, as some have proposed, by fiat (Sehm & Ragert, 2013).

Exogenous brain stimulation is not the only method of modulating brain functioning and performance. Cognitive training, exercise, and "nutriceuticals" can also produce benefits in enhancing learning and performance. Given that these methods can produce cognitive gains independently, it is possible that larger benefits may be afforded by pairing one (or more) of these methodologies with tDCS. However, there is little research on the possible synergistic effects of tDCS with other performance enhancement methods.

In conclusion, we have shown that tDCS can be used to accelerate skill acquisition in a wide range of complex learning tasks. Many important issues remain to be more thoroughly addressed in future research, so that the benefits and potential costs of tDCS as a training methodology can be better understood and its effects compared to other more traditional training methods.

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KEY POINTS

- Developing expertise in work-related tasks requires extensive practice.
- Neuroergonomics research has suggested new methods that can accelerate learning and boost human performance, including noninvasive brain stimulation.
- Transcranial direct current stimulation (tDCS) is one such method.
- TDCS has been shown to accelerate skill acquisition in tasks representative of surveillance and security operations, intelligence analysis, and procedural learning in complex monitoring.
- Training with tDCS can accelerate skill acquisition in complex tasks and may provide an alternative or addition to other training methods.

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