NEUROTECHNOLOGY WITH POTENTIAL FOR COGNITIVE ENHANCEMENT: INSIGHTS INTO BRAIN STIMULATION

Andreea MELINTE
National University of Political Studies and Public Administration
30A Expozitiei Blvd., Sector 1, 012104 Bucharest, Romania

University of East London
Stratford Campus, Water Ln, London E15 4LZ, United Kingdom
melinte.andreea@yahoo.com

***Abstract**. Brain neuromodulation techniques have been used extensively in neuroscience and cognitive psychology to alter the polarity of the brain resting membrane in order to influence behavior by applying mild current stimulation to targeted areas of the scalp correspondent to pathways in the brain responsible for particular functions. By these means, researchers have observed that cognitive performance, including attention, executive function, working memory and even language, could be enhanced or impaired according to the type of current applied to targeted area of the brain. Likewise, motor skills would be altered when the motor pathways were being targeted at the site of the stimulation. A number of studies have gone further to suggest that the effects elicited by this mild brain stimulation go beyond the time of the actual experiment and have the potential for long-lasting benefits in patients suffering from aphasia, depression, stress-related mental disorders, to name just a few. The positive results obtained by noninvasive brain stimulation are not limited however to mental health conditions, a growing literature has looked at how this intervention can be used in healthy participants to improve performance, reduce stress-related conditions or potentiate positive emotions. This paper is a review of one of these neuromodulatory techniques, transcranial direct current stimulation (tDCS) and its effects on cognitive performance, specifically face and object processing. In the absence of adverse effects and due to its relatively easy set-up, tDCS interventions have been used successfully in non-clinical protocols, becoming over the last two decades extremely popular outside the neuroscience laboratory, with private internet companies capitalizing on its success and making tDCS kits available for a wide spectrum of applications.*

***Keywords**: neuromodulation; cognition; tDCS; noninvasive brain stimulation; face processing; object processing;*

Introduction

In our daily interactions, object and face recognition are of crucial importance, allowing us to differentiate between individuals, decipher emotions in facial expressions, making sense of the world around us. Over the last decades, face processing has made the subject of numerous cognitive neuroscience and neuroimaging studies, looking at the biological underpinnings of these processes. Recent research has allowed for a deeper understanding of the subject matter by uncovering the cognitive and developmental mechanisms of object and face processing.

Surrounded by a multitude of visual stimuli, we recognize different classes of objects by combining their structural components, piecing the features together to identify an object in its entirety (Rivolta, 2016). The same process is true for faces, where by recognizing a component in isolation, the nose for example, can help identify the person it belongs to. Through evolution, we began to develop the capacity to perceive a face holistically, not merely as a sum of its components. The hypothesis that face processing involves a holistic approach, rather than parts-to-whole relationship, has been confirmed over time by researchers (Yin, 1969; Tanaka & Farah, 1993; Robbins & McKone, 2007; Le Grand et al., 2004).

During face recognition, the human visual system processes facial features, integrating them by gestalt principles, also known as holistic face processing. Behavioral studies paradigms like the composite effect and the part-whole effect have been providing evidence to support the holistic processing hypothesis. Composite effect refers to the ability to determine whether two identical top face halves are considered the same (McKone, 2008). The task becomes even more difficult, empirical evidence have shown, when the two identical top halves are paired with different bottom halves, suggesting that the whole-face context impacts of the recognition of facial features in one half of the face. The difficulty of recognizing familiar faces from isolated features has been referred to as the part-whole effect (Tanaka & Farah, 1993). The composite and part-whole effects suggest that features, rather than being recognized and processed independently, are seen holistically.

Human faces are multidimensional sources of information, with at least two levels of processing. A first one, relying on attributes found in every face, has a role in distinguishing between faces and objects. Research studies have shown that infants track face-like stimuli for longer times than non-face patterns (Farroni et al., 2005), while adults look firstly and for longer periods of time at face stimuli, than complex objects (Crouzet, Kirchner & Thorpe, 2010). All faces, supposedly, share the first-order information and to differentiate between them requires a second level of information relating to the variation existing between faces (Freire, Lee & Symons, 2000). There are three stages associated with face recognition (Maurer, 2002): detection, holistic processing and face discrimination.

Holistic processes can, however, be distinguished to a certain extent from second-order information when it comes to identifying familiar faces, compared to unfamiliar ones (Bruce et al., 1999; Megreya & Burton, 2006). When assessing familiar faces, changes in the viewpoint and expressions do not hinder accurate recognition but it does decrease the ability to recognize unfamiliar faces (Hancock, Bruce & Burton, 2000). Holistic processing, however, has been shown to influence the recognition of both familiar (Young, Hellawell & Hay, 1987) and unfamiliar faces (Le Grand et al., 2004), irrespective of viewpoint (McKone, 2008) or facial expression (Calder, Young, Keane & Dean, 2000). Moreover, research into contrast-reversed faces revealed that holistic processing is not impaired by contrast-reversal (Hole, George & Dunsmore, 1999) though it does disrupt individual recognition (Kemp, McManus & Piggot, 1990).

A study by Tsao and Livingstone (2008) looking at face perception has posited that holistic processing occurs prior to individual discrimination. In the case of inverted faces, a desensitization to second-order information takes place (Collishaw & Hole, 2000), impacting on the discrimination of inverted faces. Consequently, should holistic processing have a role in extracting first-order information then a deterioration in detecting faces would also be registered.

Neural underlying structures of face processing

The special status of face processing has been the focus of research of cognitive neuroscientists interested in identifying the areas in the brain responsible for face processing. Technological developments such as functional magnetic resonance imaging (fMRI) have identified certain neural regions that respond strongly to faces, more than they do to objects, such as the Fusiform Face Area (FFA), localized within the human temporal lobe (Kanwisher et al., 1997). Future studies have confirmed the findings, proving that the FFA is the locus of holistic face processing (Liu et al., 2009; Yovel & Kanwisher, 2005).

The occipital face area (OFA), located in the occipital lobe, appears to have a role in the acknowledgement of facial features (Gauthier et al., 2000), the superior temporal sulcus (STS) in that of the dynamic of facial reactions and the anterior temporal face patch (ATFP), within the anterior temporal lobe, of facial identity (Gobbini & Haxby, 2007; Haxby et al., 2000). It is not solely by fMRI that the importance of these regions has been established, studies on the pathology of the neural face structures indicate that these play a causal role in face recognition (Dalrymple et al., 2011; Rossion, 2014) but not in other visual classes (Pitcher et al., 2011). Considerations in support of these findings are, on the one hand, that faces, more than other non-face stimuli, are identified at an individual level and, on the other hand, that humans are more experienced at recognizing faces (Gauthier & Tarr, 2002). Non-face objects however, generate an activation of face-selective brain regions when recognized at a subordinate level rather than a basic one. Moreover, increased recruitment of the FFA has been shown to be characteristic of expertise in non-face objects (Gauthier et al., 1997).

Most human beings are capable of easily recognizing hundreds of familiar faces. However, there is a very small proportion of the general population, about 2–3%, that has severe difficulties in recognizing familiar faces (Bowles et al., 2009). This impairment is known as congenital prosopagnosia (CP) (Behrmann & Avidan, 2005; Duchaine, 2000; Rivolta, Palermo, Schmalzl, & Coltheart, 2012). Individuals with CP, as opposed to the ones with acquired prosopagnosia (AP), who are not able to recognize faces as a result of a brain injury (Bodamer, 1947), never had the ability of recognizing faces (Avidan et al, 2011; Duchaine et al., 2007; Duchaine & Nakayama, 2005). Another characteristic of people suffering from CP is impairment in non-face object recognition (Behrmann et al., 2005; Dinkelacker et al., 2010; Duchaine et al., 2007).

Research into clinical cases like CP and AP have shown how essential being able to recognize faces and facial expressions is to social integration, enabling efficient communication and conformist behavior (Blair, 2003). Pathology of these functions has been observed in patients with schizophrenia (Kohler et al., 2003), psychopathy (Hastings et al., 2008), in the autism spectrum disorder (Law Smith et al., 2010) and with brain injury (Babbage et al., 2011). However, some of the great progress made in the study of prosopagnosia over the last decades has been characterized by a lack of general consensus in the results reported, that could be accounted for by the limited number of individuals with CP tested, the heterogeneity of cases, as well as by the different pattern of experimental tasks participants were requested to perform.

tDCS

Amongst the few interventions that have the potential to ameliorate the cognitive deficits associated with the symptoms in CP and AP is tDCS, a noninvasive technique involving a mild constant current stimulation (usually 1-2 mA) of the cerebral cortex by applying electrodes to the scalp surface. While anodal stimulation is believed to have excitatory effects on targeted brain regions, cathodal stimulation triggers inhibitory effects (Nitsche et al., 2003) due to a shift in membrane potential towards depolarization and hyper polarization respectively, similar to neuroplastic alterations of cortical function (Keeser et al., 2011; Kuo & Nitsche, 2012).

Though studies into the effects of anodal and cathodal stimulation on human behavior have been inconsistent, some of the results did show that anodal stimulation can enhance human cognitive abilities (Kuo & Nitsche, 2012; Barbieri et al., 2016) and when applied to the dorsolateral prefrontal cortex (DLPFC) it enhanced cognitive functions, including verbal skills, executive function and memory (Sparing et al., 2008; Dockery et al., 2009). Long-lasting benefits of tDCS were obtained over extended or multiple sessions, thus illustrating the potential for treating and improving cognitive deficits (Nitsche et al., 2009).

TDCS has a role in changing the excitability of the cortex resting membrane, resulting in depolarization or hyperpolarization respectively (Bindman et al., 1964; Creutzfeldt et al., 1962). A short session of tDCS can result in after-effects on the plasticity of the membrane that resemble long-term-potentiation (LTP) and long-term-depression (LTD) (Liebetanz et al., 2002; Nitsche et al., 2003), by altering calcium (Ca+) electrons, mediated by N-methyl-D-aspartate receptor (NMDA-R) (Barbieri et al., 2016). According to the literature, LTP is characteristic to cathodal electric stimulation, while LTD is typical to anodal stimulation (Fregni et al., 2015). Anodal tDCS (a-tDCS) has been shown to increase motor and cognitive skills in healthy participants, when stimulation was applied to the motor cortex (Nitsche et al., 2003) and the parietal cortex respectively (Roy et al., 2015). An enhanced performance of working memory has been achieved by applying a-tDCS to the dorso-lateral-prefrontal cortex (DLPFC) in healthy participants (Fregni et al, 2005), as well as in patients suffering from schizophrenia (Hoy et al., 2014; Shin et al., 2015), and reduced depressive states in chronic depression patients (Dell'Osso et al., 2012).

The positive results obtained with tDCS have generated great interest among researchers into the cognitive, neurological and clinical effects, with very few applications however to face processing, despite the great body of evidence provided by studies into cognitive (Bruce and Young, 1986), neural (Haxby et al., 2001) and clinical studies (Palermo et al., 2011), that suggest processing face stimuli is mediated by the same systems. A study that looked into the modulating effects of face processing in healthy controls applied transcranial Random Noise Stimulation (tRNS), a type of tCS in which the stimulation of low-intensity current is varied randomly (Terney et al., 2008), concluded that face perception skills are improved in individuals that received the stimulation (Romanska et al., 2015). Recent studies have shown that delivering a-tDCS over the orbito-frontal cortex (OFC) (Willis et al., 2015) enhances recognition of facial expressions in healthy controls. Research into the potential positive effects and various applications of tDCS, while laying the foundation by exploring some of the domains the electrical stimulation can be used in, has left insufficiently explored areas. One of these areas is the contribution of a-tDCS in the recognition of face stimuli in a random population sample by modulating behaviors responsible for processing faces and objects.

Despite the progress made in the area of neuromodulation in general and its impact on face perception specifically, there are still theoretical and methodological aspects, as well as clinical, that can be explored. One such aspect would be looking for more evidence that the occipito-temporal lobe is specific to face processing rather than to other types of non-facial stimuli. While stimulating adjacent areas of the lateral occipital cortex by administering Transcranial Magnetic Stimulation (TMS) has resulted in impairments in the perception of faces, objects and other visual stimuli (Dilks et al., 2013; Pitcher et al., 2007), developing technologies that can result in an enhancement of visual perception for various categories of face and non-face stimuli is paramount.

Moreover, as memory has an important role in determining the performance of typical subjects in recognizing faces, determining if neuromodulation is not only impacting on face perception (Romanska et al., 2015), but also on the memory for faces, can reveal important insights into how the mechanisms of visual perception and memory are interconnected. On the basis of face-perception skills being circumscribed to a process that relies on the interpretation of facial features, with little contribution from the memory system, retaining and retrieving information on face identity is incumbent on face-memory performance (Dalrymple et al., 2014). The dissociation of these two processing systems in clinical subjects (Barton, 2008; Dalrymple et al., 2014), lends itself to further explorations into the enhancements brought about by tDCS.

An important factor to be taken into consideration when assessing task performance skills in tDCS experiments is the time the stimulation is applied in relation to task execution. Delivering a-tDCS to the motor cortex during a motor learning task has proved to be more effective than in the case of the stimulation occurring before the learning session (Kuo et al., 2008; Nitsche, et al., 2003; Stagg et al., 2011). However, delivering a-tDCS over the primary visual cortex before a discrimination task has generated stronger effects than when applied during task execution (Pirulli et al., 2013).

Though a-tDCS is believed to improve performance as opposed to c-tDCS, a recent study has shown (Constantino et al., 2017) that an inhibitory stimulation with c-tDCS does not always inhibit performance. The effects should be considered in relation to the timing and the application parameters that could alter the state of cortical networks carrying out a task. The application of a tDCS protocol that induces a depression in cortical activity over a specific stimulated area might result in increased sensitivity in visual performance. This is a further example of how the nervous system maintains a dynamic state to preserve performance in different environments.

Task performance was enhanced by c-tDCS when participants were administered the protocol prior to anodal stimulation as reported by studies into motor functions (Christova et al., 2015), while a 22 minutes with 1.5 mA over the occipital cortex improved performance in visual discrimination tasks (Pirulli et al., 2014), suggesting that the brain is regulating its activity, aiming to restore homeostasis following cortical depression as a result of c-tDCS. In this case the outcome is an enhanced excitability. Moreover, the effects of tDCS are much widespread than the area targeted by the electrode, impacting adjacent cortical and subcortical networks at the same time (Bestmann et al. 2015), modulation of distant networks having been also reported by neuroimaging studies (Keeser et al., 2011).

Conclusions

Research into tDCS interventions are still inconclusive and though consensus has not been reached regarding its effectiveness, there is a great body of evidence suggesting that within certain parameters the protocol cannot only improve symptoms of clinical cases but has also been used successfully to elicit positive outcomes in healthy controls. These findings have great implications not only for future directions in neuroscience and cognitive psychology but also for organizations, where a slight increase in cognitive processes, be it attention, working memory or perception, for individuals performing high-risk decision roles, can make the difference between business as usual and an impasse that could affect economies or the security of thousands.

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