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Improved reading measures in adults with dyslexia following transcranial direct current stimulation treatment

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ABSTRACT

To better understand the contribution of the dorsal system to word reading, we explored transcranial direct current stimulation (tDCS) effects when adults with developmental dyslexia received active stimulation over the visual extrastriate area MT/V5, which is dominated by magnocellular input. Stimulation was administered in 5 sessions spread over two weeks, and reading speed and accuracy as well as reading fluency were assessed before, immediately after, and a week after the end of the treatment. A control group of adults with developmental dyslexia matched for age, gender, reading level, vocabulary and block-design WAIS-III sub-tests and reading level was exposed to the same protocol but with sham stimulation. The results revealed that active, but not sham stimulation, significantly improved reading speed and fluency. This finding suggests that the dorsal stream may play a role in efficient retrieval from the orthographic input lexicon in the lexical route. It also underscores the potential of tDCS as an intervention tool for improving reading speed, at least in adults with developmental dyslexia.

1. Introduction

Low literacy is termed “developmental dyslexia” when reading is significantly lower than expected as regards age, education and intelligence, and is usually accompanied by other symptoms such as reduced coordination, right–left confusion, and/or poor sequencing typical of a neurological syndrome. Five to ten percent of children, boys more often than girls, are diagnosed with developmental dyslexia (Stein, 2001). Reading requires good phonological skills to pronounce unfamiliar words using letter-sound transformation rules, and good orthographic abilities to identify the visual forms of words enabling direct access to the lexicon.

Reading is a complex cognitive process requiring the simultaneous activity of several neurological systems. Any one of these systems can be impaired to various degrees, which impacts on the functioning of the other systems. This helps explain why reading difficulties can manifest in a variety of phenotypes, any number of which can exist in a given individual. Thus, the many theories attempting to account for dyslexia do not necessarily contradict each other, but may explain different facets of reading impairment. A number of models have been proposed to explain the fundamental cause of dyslexia based on examinations of the visual system, the auditory system, the motor system, and the attentional system. To date, the phonological deficit theory has received the most support (Liberman et al., 1989; Ramus et al., 2003, 2013; Snowling, 2000). Other accounts include rapid auditory processing theory (Tallal, 1980, 2000; Tallal et al., 1993), cerebellar theory (Nicolson and Fawcett, 1990; Nicolson et al., 2001), attentional theory (Shaywitz and Shaywitz, 2008), and magnocellular deficit theory (Galaburda et al., 1994; Livingstone et al., 1991; Lovegrove et al., 1980; Stein, 2001; Stein and Walsh, 1997).

The current study was designed within the framework of the magnocellular deficit theory (Stein, 2012) which is grounded in a visual and attentional approach. The magnocellular visual network is a distinct perceptual pathway projecting from the LGN to primary visual areas, and carries most of the visual information that is extended dorsally toward the parietal cortex. This extended magnocellular-dominated dorsal stream is critical primarily for detecting spatial relationships as well as rapid changes, hence enabling sensitivity to motion (Ungerleider and Haxby, 1994), and is considered important for intact reading (Stein and Walsh, 1997). The magnocellular function was reported to be correlated with oral reading speed in unimpaired readers as well, thus testifying to the link between reduced oral reading speed and impairment in visual tasks dependent on the magnocellular system (Au and Lovegrove, 2001; Conlon et al., 2004; Cornelissen et al., 1998). According to this approach, developmental reading impairment, at least in some individuals, is posited to be an impairment in magnocellular cell development during the embryonic stage, and is attributed to genetic mutations (Stein and Talcott, 1999; Stein

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and Walsh, 1997).

Various experimental findings involving both impaired (Cornelissen et al., 1995; Demb et al., 1998; Eden et al., 1996; Gori et al., 2014; Livingstone et al., 1991; Lovegrove et al., 1980; Martínez et al., 2013) and unimpaired readers (Au and Lovegrove, 2001; Conlon et al., 2004; Cornelissen et al., 1998; Richlan et al., 2011) support the idea of magnocellular involvement in reading. However, the role of a putative magnocellular deficit in dyslexia is hotly debated (Amitay et al., 2002; Olulade et al., 2013; Ramus et al., 2003; Sperling et al., 2005) and a convincing causal mechanism explaining the way in which the magnocellular system contributes to accurate reading is still triggering much research.

One mechanism ascribes a role to the dorsal system in accurate letter position encoding (Cornelissen et al., 1998), possibly through precise shifting of visual attention during fixation (Vidyasagar, 1999). The visual extrastriate area V5, dominated by magnocellular input, is thought to provide attentional feedback which modulates incoming visual information to V1, and thus enabling the selection of sequential locations for processing during fixation (Vidyasagar, 1999, 2004, 2013).

The importance of V5 as support for motion detection, a basic function of the magnocellular system was reported in a study involving the induction of specific and reversible motion blindness by magnetic stimulation of this area (Beckers and Homberg, 1992). A more recent magnetic stimulation study indicated a causal role for the left V5 in word identification (Laycock et al., 2009). A recent study in our lab (Levy et al., 2010) found that the dorsal stream, including V5, contributes exclusively to real-word identification. These findings support the claim of a role for the dorsal stream in the lexical route that enables retrieval from the visual-orthographic input lexicon.

An alternative approach to V5 involvement in reading and dyslexia was recently proposed by Olulade et al. (2013), who argue that abnormal visual motion processing is not a cause but rather an outcome of dyslexia. This is consistent with previous claims that magnocellular dysfunction may be a side effect of dyslexia which emerges along with other deficits that are the primary cause of the reading problem (Eden and Zeffiro, 1998; McLean et al., 2011; Ramus, 2004).

Thus critics of the magnocellular reading theory argue for an epiphenomenal rather than a causative link between dyslexia and dorsal stream dysfunction. This underscores the need for more causative and intervention-based research to clearly identify the role of dorsal stream function in reading. The current study was designed to examine the contribution of magnocellular function to reading as well as to illustrate the potential of non-invasive brain stimulation as a tool to improve reading fluency. If stimulating a magnocellular-dominated brain area improves text reading fluency, this would provide additional evidence supporting magnocellular involvement in the natural process of reading.

The only previous study that applied transcranial magnetic stimulation (TMS) to adults with developmental dyslexia was conducted by Costanzo et al. (2013) who tested the role of high frequency TMS over language areas that are known to be underactive in dyslexia in performance improvement. A sample of 10 adults with developmental dyslexia underwent 6 TMS sessions (in 2 days) that stimulated the left and right IPL, the left and right STG, the vertex as a control area and sham. Reading tests of words, nonwords and texts followed the stimulation sessions. The pattern of results was complex; however, they found improvement in text reading accuracy and faster nonword reading. This is certainly a promising line of research. Nevertheless, we considered that TMS at such frequencies and intensities (100% of motor threshold, 500 pulses for 7 min) might not be the ideal treatment for dyslexia since many subjects report discomfort and pain using similar protocols (Borckardt et al., 2013). By contrast, transcranial direct current stimulation (tDCS) is relatively painless and silent (Nitsche and Paulus, 2001).

tDCS is a noninvasive weak-current brain stimulation technique that can facilitate (anodal electrode) or inhibit (cathodal electrode) cortical activity, thus making it possible to study the causal relations between brain activity and behavior (Nitsche et al., 2008). Unlike TMS which is typically used to disrupt neuronal activities at specific cortical locations, anodal tDCS has the potential to enhance activity in targeted brain areas. A recent study showed that tDCS over Broca's area improved phonemic and semantic fluency in healthy adults (Cattaneo et al., 2011), whereas tDCS over Wernicke's area improved picture naming in aphasic stroke patients that lasted several weeks post-stimulation (Fiori et al., 2011). In the first study investigating the use of this technique to improve reading efficiency in non-dyslexic but slow readers (Turkeltaub et al., 2012), a single tDCS session over the posterior temporal cortex improved reading of real and non-words.

So far there have been no studies of tDCS in individuals with dyslexia. In addition, previous studies of magnocellular system involvement in reading have focused almost exclusively on single words and non-words rather than text reading fluency, arguably a more useful and essential capacity for all readers and, together with comprehension, one of the major goals of remedial reading interventions. This is especially true for languages other than English in which fluency rather than accuracy is the key discriminator of developmental and individual differences in reading ability (Shany and Share, 2011).

The current study attempted to address both issues and investigated the influence of tDCS on text reading fluency and accuracy. Based on previous magnetic stimulation findings (Laycock et al., 2009), the left area V5 was selected for stimulation. Anodal tDCS over the left V5 was expected to facilitate dorsal route activity as manifested in improved oral text reading speed. Because increased reading speed would be counterproductive if it involved a parallel increase in errors, we expected that the improved reading speed would not be attained at the cost of reduced accuracy. The specificity of V5 stimulation to orthographic material was tested by its effect on visual scanning of nonverbal material (symbol search). An improved visual scanning score together with an improved oral reading rate would suggest a nonspecific facilitation of information processing speed. On the other hand, selective improvement of text reading and fluency but not nonverbal material would suggest a more specific influence of V5 activity on orthographic processing speed.

Because the importance of tDCS as a rehabilitation tool depends on its long-term effects on behavior, we utilized repeated anodal stimulation, and tested oral reading fluency and accuracy both immediately after stimulation and about one week after the final tDCS session (after Cohen Kadosh et al., 2010).

2. Materials and methods

2.1. Subjects

Twenty-three subjects were recruited by ads posted on campus. Males and females, 18 years and older, with Hebrew as their native language and no neurological or psychiatric conditions met the study criteria. All provided a psycho-didactic evaluation which found reading disability without ADHD. All were paid for their participation, with the exception of one subject who elected to receive course credit. Of the 23 initial subjects, 19 completed the full study that included 6 sessions in the laboratory for one month. The subjects were randomly assigned to two groups (active and sham stimulation). Verbal and performance IQ sub-scales were estimated using the vocabulary and block design subtests of the