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.

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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

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

Table 1
Mean demographic, reading, vocabulary and block design sub-tests scores (and SD) of the active and sham stimulation groups.

	N	Gender	Age	Years of education	Reading speed, words per minute (WPM)	Vocabulary (max. 66)	Block design (max. 68)
Anodal	10	4 Males	27.2(7.2)	13.8(1.5)	99.2 (26.7)	50.8(8.3)	48.8(10.9)
Sham	9	5 Males	24.5(5.2)	13.4(1.3)	98.1 (33.9)	50.1(5.8)	54.0(11.4)

Vocabulary scores are raw scores on the Hebrew version of WAIS-III vocabulary subtest; block design scores are raw scores on WAIS-III block design subtest. The mean number of words per minute (WPM) is significantly lower than the average WPM for Hebrew for adults free of dyslexia which is 187 (SD 29), (Trauzettel-Klosinski and Dietz, 2012).

Wechsler Adult Intelligence Scale, 3rd edition (Wechsler, 1997). The two groups did not differ in terms of demographics, Vocabulary and Block Design subtests or baseline reading level (see Table 1).

A repeated measure mixed design ANOVA for the Wechsler sub-tests comparisons was conducted with group (anodal and sham) as the between subject factor and task (vocabulary and block design) as the within subject factor. None of the main effects or interactions were significant: group (F(1,18)=0.09, NS; task F(1,18)=0.03, NS; group by task F(1,18)=0.37, NS).

Vocabulary scores did not differ between the two groups, with the anodal group obtaining a score of 50.8($\pm$8.3), and the sham group 50.1($\pm$5.8), out of the possible 66 points, $p > 0.839$. Both scores reflect above average abilities and are approximately equivalent to the 84th percentile rank (range 50th–98th) and a Verbal IQ (VIQ) of 115 (range 100–130). A slightly larger discrepancy was found on the block design subtest where the anodal group scored 48.8($\pm$10.9) and the sham group 54.0($\pm$11.4), reflecting high-average to above average abilities. These scores are approximately equivalent to the 75th percentile rank (range 63rd–95th) and a Performance IQ (PIQ) of 110 (range 105–125) for the tDCS group, to 91st percentile rank (range 75th–99th) and a PIQ of 120 (range 110–135) for the sham group. The non-significant advantage of the sham group in the block design subtest was not expected to have any effect on reading speed or other verbal tests used in this study. Moreover, even if the PIQ had had an effect on study measures, it would have given an advantage to the sham group, making findings in the tDCS group all the more convincing.

Pre-experimental reading speed of both groups was 98–99 WPM, which is the average Hebrew reading speed in the 5th grade (Shany et al., 2006). Thus, in spite of their above-average vocabulary block design subtests scores, both groups displayed impaired oral reading speed.

2.2. Experimental design

The experimental design consisted of comparing stimulation effects as a between-subjects factor (anodal and sham) on repeated measures of oral reading speed and accuracy at 3 time points (pre-stimulation, immediately after stimulation and one week after the end of stimulation). We also compared in a $2 \times 2 \times 3$ mixed design RM-ANOVA anodal and sham groups before and immediately after stimulation on reading errors, rapid automatized naming (RAN) letter naming and number naming and the WAIS-III symbol search.

2.3. Tests administered

2.3.1. Oral reading

Three one-page-long texts at the 9th grade level were used (Tov-Li, 1999). These texts are routinely used in evaluations of reading difficulties in Israel. Subjects read aloud one of the texts prior to tDCS stimulation and the others immediately after, and a week after the five stimulation sessions. Text order was counterbalanced between subjects to rule out effects of subtle difficulty

differences between them. Reading time was measured and errors were noted.

2.3.2. RAN

Rapid automatized naming (RAN; Denckla and Rudel, 1976) is a test of reading fluency commonly used to identify reading disabilities, and is standardized in many languages including Hebrew (Ben-Dror and Shany, 2002). It contains 50 letters (part 1) or 50 numbers (part 2), printed in five lines of 10 items each, which are read aloud from right to left (Hebrew letters), or from left to right (numbers) at the greatest possible speed. Naming time was measured.

2.3.3. Symbol search

The symbol search subtest of the Wechsler Adult Intelligence Scale, 3rd edition (Wechsler, 1997) was used. It consists of a paper and pencil test of visual, non-verbal attention and scanning ability that also reflects information processing speed. Each page has 15 lines of symbols. Each line is searched for one of two symbols. A "yes" square is checked if one of the symbols appears and a "no" square if none of them appear. Subjects have two minutes to complete as many lines as possible. The page order presented to subjects was shuffled between the first and second administration to rule out possible memory effects.

2.4. Transcranial direct current stimulation (tDCS)

A battery activated direct current stimulator (Megastim eldith DC-Stimulator, neuroConn GmbH, http://www.neuroconn.com/) administered a 1.5 mA current for 20 min via two sponge-covered electrodes soaked in salt water prior to administration. Previous studies (Poreisz et al., 2007) have shown this current to be safe in healthy individuals. The anode (5×5 cm^2) was placed over the left V5 area, and the cathode (5×7 cm^2) was placed over the right orbito-frontal cortex (right eyebrow). The anode was placed 3.5 cm above and 6 cm left of the mastoid inion in the sagittal plane (the average location of two previous tDCS studies: Antal et al., 2004; Cowey et al., 2013).

The stimulated region, V5/MT has an important part in supporting motion detection (Beckers and Homberg, 1992) and word recognition (Laycock et al., 2019) in healthy brains. Crucially, here it was selected for anodal stimulation since previous fMRI studies reported significant reduced activity in this area in dyslexics brains (Demb et al., 1998; Eden et al., 1996).

2.4.1. Sham stimulation

Identical electrodes were placed in the same locations with the same current strength as the real tDCS stimulation but current was automatically shut off after 15 s. Therefore, subjects initially felt the tingling sensation typical of real stimulation but thereafter received no current (Jacobson et al., 2011).

2.5. Procedure

Subjects brought an evaluation report indicating reading disability as a prerequisite for participating in the study. They were

randomly assigned to one of the two stimulation groups. They read an informed consent form and signed it (the form was read to those who struggled with this reading). Subjects answered an oral questionnaire about ADHD symptoms and were questioned regarding use of stimulant medication for ADHD. Then the RAN-letter and RAN-number tests and the symbol search test were administered, followed by oral reading of a one-page-long text. They then underwent tDCS (active or sham) and were discharged. During the next three sessions subjects were only administered stimulation. On the fifth session, tDCS was administered followed by the letter- and number-RAN, symbol search, and oral text reading. In addition, the vocabulary and block design subtests of the WAIS-III were administered to estimate verbal and nonverbal intelligence. The five stimulation sessions lasted about 2 weeks. About a week later, subjects came for the final oral text reading.

3. Results

Four subjects dropped out of the study before completion. Analysis was thus done on 19 adults with dyslexia (10 women), 10 in the experimental group and 9 in the control group.

Although the RAN and symbol search are standardized tests, we used raw scores for increased accuracy; namely, the number of seconds required to complete the naming of 50 letters or 50 numbers on the RAN test, and the number of correct answers minus the number of errors on the symbol search subtest. Thus, improved performance after tDCS would manifest in RAN by a shorter completion time, and in the symbol search by a greater number of lines completed in the two minutes allotted.

A repeated measure mixed design $2 \times 2 \times 3$ ANOVA for RAN and symbol search measures was conducted with group (anodal and sham) as the between subject factor and time (pre-stimulation, immediately after stimulation) and task (RAN letters, RAN numbers and symbol search) as the within subject factors. There was a main effect for task, which was expected since the tasks were measured with different units ($F(2,16)=17.05$, $p=0.0002$). The group effect ($F(1,17)=0.47$, NS), time effect ($F(1,17)=0.24$, NS) and group by task ($F(2,16)=2.57$, NS) did not reach significance. Crucially, a significant group $\times$ time $\times$ task interaction was found ($F(2, 16)=6.05$; $p=0.011$). To interpret the 3-way interaction, we conducted 3 mixed analyses for each measure separately, later followed by posthoc comparisons with Bonferroni corrections. There was a significant interaction of stimulation group and time for the RAN number test ($F(1,17)=5.54$, $p=0.03$). Number naming speed was reduced from 23.7 to 20.3 s in the anodal group ($t(9)=2.89$, $p=0.006$), but barely changed (from 21.2 to 21.6 s, $t(8)=0.37$, NS) in the sham group. The interaction of stimulation group and time for the RAN letter test was marginally significant ($F(1,17)=3.83$, $p=0.06$), but the trend was similar to what we observed with the RAN number test: RAN letter naming speed was decreased from 25.5 to 20.8 s in the anodal group, but again barely changed (from 25.7 to 24.9) in the sham group. For the symbol search task, there was a significant main effect for time of measurement ($F(1,17)=9.95$, $p=0.006$) reflecting improvement in both stimulation

groups at time 2, immediately after the stimulation sessions; however there was no significant time $\times$ stimulation group interaction as was found on the RAN numbers task. Table 2 presents the RAN and symbol search scores before and immediately after stimulation.

To evaluate stimulation effects on reading, a mixed design repeated measures 2×3 ANOVA with stimulation group (anodal, sham) as the between subject factor and time (pre, immediately after or 1 week after stimulation) as within subject variable was conducted for reading speed and reading errors.

For oral reading speed, there were no significant effects for group or time, but the group $\times$ time interaction reached significance ($F(2,34)=3.53$, $p=0.04$). To interpret this interaction, we compared the two groups separately in each time point, using post-hoc comparisons with a Bonferroni correction. Reading speed before stimulation ($t(17)=0.7$, NS) and immediately after stimulation ($t(17)=1.3$, NS) did not differ significantly between the stimulation groups, however there was a significant difference ($t(17)=2.61$, $p=0.01$) in reading speed between the anodal group reading speed (114.3 WPM) and the sham group (91.3 WPM) one week after stimulation, see Fig. 1. There were no main effects or interactions in the reading error measure, which reflected a low and stable level of errors (ranging from 4.8 to 6 errors in all conditions); hence the faster reading rate after stimulation did not affect reading accuracy.

4. Discussion

The current study investigated the effects of non-invasive brain stimulation of the magnocellular system on text reading speed and accuracy. Based on previous magnetic stimulation findings (Laycock et al., 2009), the left area V5 was selected for stimulation. After 5 days of anodal tDCS over the left V5, we observed improved oral text reading as well as improved letter-naming and number-naming speed. RAN letter- and number naming speeds are considered highly specific predictors of reading fluency (Norton and Wolf, 2012; Denckla and Rudel, 1976), and it was suggested (Savage and Frederickson, 2005) that rapid digit naming and phonological processing are distinct contributors to different aspects of reading in poor readers.

The increased reading speed did not reduce accuracy, which was maintained and even increased after one week of stimulation. Average scores on the symbol search test improved in both groups on the post treatment test, but there was no stimulation group and time interaction. Therefore, the visual scanning rate of nonverbal material was not directly affected by anodal stimulation of left area V5, and the improved RAN and reading fluency measures cannot be accounted for by a nonspecific enhancement of information processing speed. Rather, the selective improvement of text reading and letter- and number-naming speed but not of symbol search suggests a more specific influence of V5 activity on orthographic processing speed, in line with the magnocellular theory of reading (Stein, 2001).

In the introduction we summarized current dyslexia theories

Table 2
Comparing anodal and sham tDCS groups on rapid automatized naming and symbol search (means and SD).

	RAN letters (pre)	RAN letters (immediately after)	RAN numbers (pre)	RAN numbers (immediately after)	Symbol search (pre)	Symbol search (immediately after)
Anodal	25.5 (7.7)	20.8 (3.3)	23.7 (7.6)	20.3 (5.7)	31.5 (10.0)	35.6 (9.9)
Sham	25.7 (6.0)	24.9 (6.0)	21.2 (4.4)	21.6 (3.6)	33.3 (12.0)	36.0 (10.1)

RAN – rapid automatized naming; (pre) – tested before tDCS began; (immediately after) – tested immediately after 5 tDCS sessions; RAN letters and RAN numbers=reading speed in seconds; symbol search=number of correct answers minus number of errors.
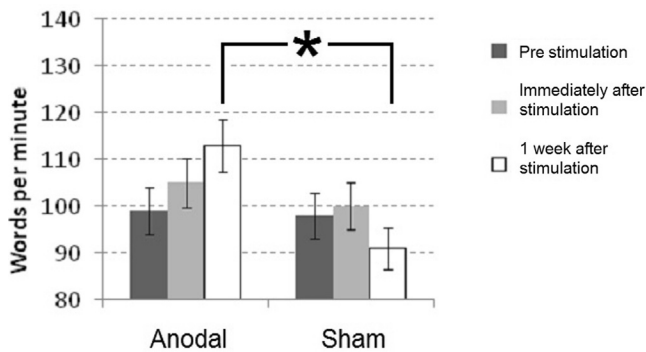
Fig. 1. tDCS effects on oral reading speed (words per minute). Error bars represent the standard error of the mean.

and proposed that even alternative theories acknowledge a phonological deficit as a crucial mediator between other factors and reading impairment (Tallal, 1980; Nicolson et al., 2001; Stein, 2001). However, Ramus and Szenkovits (2008) suggested that the phonological deficit may not lie in the representations themselves, but rather in some cognitive or perceptual skills that apply to them in certain tasks (Berent et al., 2012; Ramus and Ahissar, 2012). The implications of Ramus and Szenkovits (2008)'s view is that the existence of phonological impairment does not rule out other dyslexia mechanisms, such as cognitive or perceptual skills. Our results cannot rule out alternative, co-existing dyslexia theories. However the magnocellular deficit theory offers the most parsimonious account to the current results. Note that the reduced activity found in the V5/MT of dyslexics brains is well documented (Demb et al., 1998; Eden et al., 1996). We selected a stimulation protocol that consistently increases activation in the stimulated area (Jacobson et al., 2011), and employed it over the assumed hypoactive V5/MT in dyslexics brains, leading to improved reading speed and fluency. The magnocellular deficit theory not only supplies the most parsimonious account of these results, but also offers a potential treatment.

The significant improvement in reading measures following anodal stimulation of V5 may thus be an indication that this area is involved in reading. However, we should interpret these findings with caution, considering the limited spatial resolution of tDCS. Modeling studies on the distributions of current produced by tDCS have shown that large currents subjacent to both stimulation and reference electrodes regardless of polarity were produced (Sadleir et al., 2010). This finding limits the ability to argue for causal effects in tDCS; however, as long as there are control experimental conditions, such as sham stimulation and control tasks, it is safe to conclude that a certain montage generated specific behavioral changes, as we show here. For rehabilitation purposes, this is certainly a desired goal.

One mechanism suggested elsewhere argues that magnocellular input and dorsal stream areas affect the accurate ordering of the letter sequence within a word (Cornelissen et al., 1998; Vidyasagar, 1999). More specifically, it was posited that the dorsal stream provides attentional feedback which modulates incoming visual information to V1, thus enabling the selection of sequential locations for processing during fixation (Laycock and Crewther, 2008; Vidyasagar, 1999; Vidyasagar and Pammer, 2010). Recently it was suggested that the well accepted phonological deficit present in many individuals with dyslexia, is a result of this visual impairment rather than the source of reading difficulties (Vidyasagar and Pammer, 2010). Further, phonological awareness and intact grapheme phoneme conversions may depend on normal visual input during development and thus on intact magnocellular

function. This idea was supported by evidence of improved phonological awareness after orthographic training (Ehri and Wilce, 1980; Johnston et al., 1996) and by imaging data showing a significant correlation between contrast responsiveness in area V5/MT and phonological awareness (Ben-Shachar et al., 2007).

The integrated model for visual processing (Bullier, 2001) claims that visual information arriving through the dorsal stream induces rapid activation of area V5 and the frontal eye field where it generates low frequency representations of global information. This information is then back-projected, via fast feedback connections, to early visual areas V1/V2 where it is used to guide parvocellular processing of the visual scene (see also Beckers and Zeki, 1995). In a similar manner, it was suggested (Levy et al., 2010) that a low pass representation of the letter string is delivered through the dorsal stream to parietal and frontal areas. This representation is back-projected to the early visual cortex and is used to prime a small set of words with similar shapes or outlines in word-form related areas. Poor magnocellular performance would impair the delivery of this top-down representation, and thus reduce its facilitating contribution. This hypothesis assumes that the dorsal route plays a role in facilitating access or retrieval from the orthographic receptive lexicon.

The stimulation montage applied in this study was successful in facilitating visual-orthographic processes involved in swift reading. To the best of our knowledge this is the first demonstration of tDCS effects on oral text reading fluency in dyslexia. It has been suggested (Fuchs et al., 2001) that oral text reading is *the* indication of reading competence and has unique advantages over single word lists. Our study therefore extends previous findings (with both impaired and unimpaired readers) by showing improved oral reading fluency of extended meaningful texts in reading impaired adults.

In a previous study we suggested associating the left hemisphere (LH) advantage for motion detection with the well-established LH specialization for word recognition (Levy et al., 2010). The magnocellular coarse representation output may be more dominant in the left hemisphere, thus making the top-down contribution more significant in that hemisphere. This advantage may help account for the fact that the role of the magnocellular system in reading was found when the *left* V5 was stimulated (TMS: Laycock et al., 2009; and tDCS in the current study).

Stimulation improved both text reading and reading fluency. It is interesting that the stimulation effect, that is the difference in scanning time between baseline and post-stimulation measure, was larger for naming letters than for naming numbers. Note that our subjects read Hebrew, which is written right-to-left. It is well established that native language shapes the attentional biases to the left or right of targets, in line with reading direction (Rinaldi et al., 2014; Spalek and Hammad, 2005). Both RAN tests that measure reading fluency are applicable to text reading (Norton and Wolf, 2012); however the right-to-left bias in Hebrew that is found only in letters and words (but not numbers), might explain the larger stimulation effects for letters compared to numbers.

One limitation of the current study was that we did not have an active tDCS control condition. It therefore cannot be ruled out that the findings may be the result of unspecific effects of brain stimulation compared to sham stimulation. However, participants in the anodal group were informed that tDCS might or might not affect their performance in either way (positive or negative). For this reason, unspecific increased or decreased levels of motivation in the anodal group cannot by itself explain the gradual and direction-specific effects found in the active stimulation group over time. Another limitation is the relatively small sample. However since the experimental and control group were homogenous and well matched for background variables, vocabulary and (impaired) reading levels this drawback may have been at least partially compensated for.

The importance of tDCS as a rehabilitation tool depends on its long-term effects on behavior, and our current findings seem promising in this regard since the improved measures were significant when tested one week after the end of the stimulation sessions. It seems tempting to apply this protocol to a younger population with developmental dyslexia, given that repeated anodal tDCS over area V5 appear to generate improvements comparable to active, prolonged and more expensive phonological training. Possibly the two mechanisms tap different components of the reading network and as such lead to improved behavioral measures. Clearly, further work needs to be done to guarantee a safe, efficient stimulation montage protocol, as well as more in-depth analyses of the stimulation frequency required to maintain the effect.

We believe that tDCS has the potential to improve text reading in adults with developmental dyslexia, but caution that the setting and circumstances deserve careful attention to avoid null findings. To strengthen our particular V5 stimulation procedure to possibly promote reading improvement, future neuroimaging studies are needed to examine the neurophysiological changes after stimulation, as well as to test other stimulation sites using richer sets of orthographic, phonological and semantic tasks. Extensive research is now needed to define the ideal tDCS parameters and the experimental requirements to achieve longer-term reading improvement in healthy and clinical populations.

Acknowledgment

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