

## Research article

# No Effect of cathodal tDCS of the posterior parietal cortex on parafoveal preprocessing of words

Lorenzo Vignali<sup>a,b,c,\*</sup>, Stefan Hawelka<sup>a</sup>, Florian Hutzler<sup>a</sup>, Fabio Richlan<sup>a</sup>

<sup>a</sup> Centre for Cognitive Neuroscience, University of Salzburg, Hellbrunnerstr. 34, 5020, Salzburg, Austria

<sup>b</sup> Center for Mind/Brain Sciences (CIMEC), University of Trento, 38068, Rovereto, TN, Italy

<sup>c</sup> International School for Advanced Studies (SISSA), 34136, Trieste, Italy

## ARTICLE INFO

## Keywords:

Bayesian hypothesis testing  
Foveal load  
Lexical decision flanker task  
Parafoveal-On-Foveal  
Parafoveal preprocessing  
Transcranial direct current stimulation

## ABSTRACT

The present study investigated the functional role of the posterior parietal cortex during the processing of parafoveally presented letter strings. To this end, we simultaneously presented two letter strings (word or pseudoword) – one foveally and one parafoveally – and asked the participants to indicate the presence of a word (i.e., lexical decision flanker task). We applied cathodal transcranial direct current stimulation (tDCS) over the posterior parietal cortex in order to establish causal links between brain activity and lexical decision performance (accuracy and latency). The results indicated that foveal stimulus difficulty affected the amount of parafoveally processed information. Bayes factor analysis showed no effects of brain stimulation suggesting that posterior parietal cathodal tDCS does not modulate attention-related processes during parafoveal preprocessing. This result is discussed in the context of recent tDCS studies on attention and performance.

## 1. Introduction

During reading, information is not only extracted from the word we are currently fixating (i.e., the word in foveal vision), but attention is also directed to parafoveal regions to the right of the fixation (when reading left to right). Both, orthographic and phonological properties are extracted from the upcoming word [1]. Models of eye movement control provide specific assumptions about how attention is deployed during reading. To illustrate, the E–Z Reader model [2–7] assumes that attention is allocated in a serial manner, to one word at a time. The SWIFT model [8,9], in contrast, considers attention as a gradient spreading across several words in parallel. It is important to note that whereas these models provide strong theoretical assumptions on attention deployment during reading, little is known about the neural correlates of attention deployment in parafoveal preprocessing. The aim of the present study is to use transcranial direct current stimulation (tDCS) in order to assess the specific functional role of brain regions involved in attention reallocation processes during parafoveal preprocessing.

Previous studies assessed the neural correlates of reading-related attentional processes [10–13]. It remains, however, unclear, whether the results of these studies are generalizable for attention deployment during parafoveal preprocessing. The reason for this limitation is that the studies aiming at investigating reading-related attentional processes

employed experimental paradigms that are, in most cases, inadequate for the study of parafoveal preprocessing. More specifically, paradigms ranged from the presentation of isolated words [10–13] to sentence reading [14]. Presenting words in isolation at different eccentricities, however, is not a valid approach to study attentional processes during parafoveal preprocessing, because during reading, words are rarely recognized and processed in isolation. Instead, during parafoveal preprocessing, foveal information of the currently fixated word and parafoveal information of the upcoming word are simultaneously available [1,15]. Conversely, sentence reading paradigms induce complexity (e.g., contextual and syntactic effects) above and beyond the main objective of investigating the attentional processes of parafoveal preprocessing.

Flanker tasks provide a feasible solution to the aforementioned problems. In a flanker task, foveally presented words are flanked by one (left- or right-sided) or two (bilateral) parafoveally presented words that can be conveniently manipulated, while keeping syntactic processing demands at a minimum. Flanker tasks were repeatedly used in combination with electroencephalography (EEG [16–20]) and proved to be a suitable tool for investigating the nature and timeline of parafoveal processing. We combined the flanker task with the lexical decision task (henceforth lexical decision flanker task). Specifically, we presented participants simultaneously with two stimuli, one centrally (i.e., foveally) and one to the right of fixation (i.e., parafoveally). The

\* Corresponding author at: Center for Mind/Brain Sciences (CIMEC), University of Trento, Corso Bettini, 31, 38068, Rovereto, Italy.

E-mail address: [lorenzo.vignali@unitn.it](mailto:lorenzo.vignali@unitn.it) (L. Vignali).

<https://doi.org/10.1016/j.neulet.2019.05.003>

Received 6 December 2018; Received in revised form 12 April 2019; Accepted 3 May 2019

Available online 04 May 2019

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stimuli were words and/or pseudowords (pronounceable letter strings with no meaning) and the four possible combinations of stimuli were: two words (WW); a word and a pseudoword (WP); a pseudoword and a word (PW); two pseudowords (PP, see 2.1.4 for further details). The task was to indicate whether one of the items was a real word (lexical decision flanker task).

To ensure parafoveal (and not foveal) processing of the flanker item we kept the presentation duration short (i.e., 180 ms) and we made use of an eye tracker to control for the position of the eyes at the moment of stimuli appearance (see Method section for details). Previous studies estimated the time needed to plan and execute a saccade to be around 180–250 ms [21,22]. Thus, a presentation duration of 180 ms is short enough to prevent eye movement towards (and foveal processing of) the parafoveal stimulus. On the other hand, the duration is long enough to process the foveal stimulus and to engage in parafoveal preprocessing. To illustrate, studies investigating the timeline of foveal word recognition measured lexical processing to occur as early as 120 ms after stimulus appearance (see [23–25]). With regard to parafoveal (pre)processing, Cohen et al. [12] demonstrated that participants were able to accurately recognize words at different eccentricities using a presentation duration of only 170 ms. Pernet, Uusvuori and Salmelin [26] reported priming effects from parafoveally presented words with a presentation duration of 187 ms. Using a flanker task with foveal and parafoveal stimuli, Dare and Shillcock [27] reported preview effects from the parafoveal stimuli with a presentations durations of 150 ms. Behaviorally we expected foveally presented words (conditions WW and WP) to be easy to recognize, thus resulting in higher accuracy rates and faster reaction times as compared to foveally presented pseudowords (conditions PW and PP).

The main objective of the present study was to assess whether there is a causal link between neural correlates of attentional processes and behavioral performance during parafoveal preprocessing. Reichle, Rayner and Pollatsek [28] – based on a comprehensive literature review – sketched the potential neural underpinnings of the mechanisms of the E-Z Reader model of eye movement control during reading. For the relocation of attention a part of the posterior parietal cortex (PPC), the intraparietal sulcus (IPS), was identified as a potential candidate for attention reallocation. Neural activation within the IPS has been associated with top-down control of visual attention [29–33]. Activation in the IPS was also proposed to guide oculomotor and visual attentional systems by mapping the behavioral priority of stimuli [34–38]. Furthermore, oculomotor planning [34,39,40], visual working memory [41–43] and the maintenance of the current state of attention [44,45] are domains in which the IPS is assumed to play a role. Accordingly, previous studies investigating shifts of attention using linguistic material [12] indicated that an area of the posterior parietal cortex (PPC) is probably involved in the control and allocation of attentional resources.

Additional evidence on the relation between regions within the PPC and attention-related processes can be found in brain stimulation studies. Non-invasive brain stimulation techniques such as transcranial direct current stimulation (tDCS) allow establishing causal links between brain activity and behavioral performance [45]. During tDCS, a weak electrical current is delivered to the outer cortical layers through electrodes placed over the scalp [46–51]. TDCS can induce changes in cortical excitability through hyperpolarization (cathodal stimulation) or depolarization (anodal stimulation) of the resting membrane potential of the stimulated neural tissue [48,52,53]. Previous tDCS studies investigating attention-related processes reported significant effects of current stimulation when applied over the PPC [14,54–61].

Following the evidence from previous neuroimaging and brain stimulation studies we considered the IPS as a putative area for the control and allocation of attentional resources during parafoveal preprocessing. We applied cathodal tDCS on two separate groups of participants in an attempt to delineate the individual contributions of the left and right IPS. We predicted that cathodal tDCS over the left and/or right IPS would inhibit processes related to the reallocation of attentional

resources towards parafoveally presented stimuli, thus negatively affecting task performance.

As part of the present study, we asked a third group of participants to perform the same experiment in fMRI. Due to the novelty of our experimental task, it was important to demonstrate parietal activation as induced by reading-related attentional processes. The fMRI findings, however, will be only briefly discussed as the assessment of neural underpinning of word recognition was beyond the scope of the present manuscript (for reviews on the topic see [62–65]).

## 1.1. Materials and methods

### 1.1.1. Participants

Forty native German speaking students (8 male, 32 female,  $M = 23.7$  years,  $SD = 2.5$  years) participated in the study. All participants were right-handed, had normal or corrected-to-normal vision and no history of neurological or psychiatric disease. Before testing, all participants gave their written informed consent and undertook a short reading test currently developed in our lab. The test required to silently read sentences and mark them as correct (e.g., “A bicycle is environmentally friendly”) or incorrect (e.g., “A travelling agency usually sells picture frames”). The incorrect statements were obvious violations of common knowledge and hence judging the correctness was easy ( $M < 1$  incorrect marking in both groups). Thus, the measure (number of correctly marked sentences within three minutes) is an index of reading speed. The preliminary norms of the test are based on a sample of 309 University students. All participants exhibited a reading rate greater than percentile 16 ( $M =$  percentile 77). The study was conducted in accordance with the Declaration of Helsinki and was approved by the ethical review committee of the University of Salzburg.

### 1.1.2. tDCS

A 1.5 mA direct current was delivered to the scalp through saline-soaked sponges. The size of the cathodal electrode was 5 x 7 cm (current density 0.043 mA/cm<sup>2</sup>) and the size of the anodal electrode was 10 x 10 cm (current density 0.015 mA/cm<sup>2</sup>) in order to effectively modulate the cortical regions beneath the cathodal but not under the anodal electrode. A battery-driven DC-stimulator Plus (NeuroConn GmbH, Ilmenau, Germany) generated the constant current flow. In the active session cathodal stimulation began with 30 s ramp-up, followed by 30 min constant current, and ended with 30 s ramp-down. In the sham session cathodal stimulation was ramped up and down only at the beginning of the session. This procedure ensured a temporary itching sensation for both active and sham stimulation sessions.

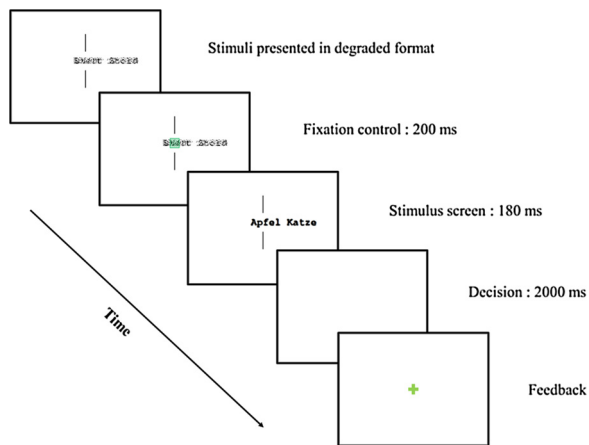
For the stimulation of the right IPS the cathodal electrode was placed over P4, whereas for the left IPS stimulation the cathodal electrode was placed over P3 (in accordance with the 10–20 international system for electrode placement). The anodal electrode was always placed over the contralateral supraorbital site.

### 1.1.3. Eye tracking

Eye movements were recorded monocularly from the right eye with an SR Research Eyelink 1000 desktop mount system (SR Research Ltd., Ottawa, Canada). For data acquisition the eye tracker’s sampling rate was set to 1 kHz and the head position was stabilized using a chin rest. At the beginning of each run the eye tracker was calibrated with a horizontal 3 points calibration routine. The calibration was considered successful if the average tracking error was below 0.5° of visual angle. The calibration routine was repeated every time the fixation control at the beginning of a trial failed (see Fig. 1). Stimulus presentation was controlled by the Experiment Builder software (SR Research Ltd., Ottawa, Canada).

### 1.1.4. Apparatus and stimuli

Participants were seated in a dimly lit room, at a distance of about 60 cm from a 21-in (53.34 cm) cathode ray tube monitor (1024 × 768



**Fig. 1.** Schematic representation of stimuli and task. Each trial started with stimuli being presented in a degraded format. A fixation of 200 ms between two vertically aligned bars triggered stimulus appearance in the undegraded format. Stimuli remained on the screen for 180 ms. Followed a blank screen of 2000 ms where button presses were recorded. Last, a feedback (red or green cross) was displayed. Stimuli are not drawn to scale.

pixel resolution, 120 Hz refresh rate). The stimulus material consisted of four different experimental conditions with one hundred trials each. Trials were presented event-related in a pseudorandomized order. Each trial was composed of two simultaneously presented stimuli (see Fig. 1), one foveally ( $n$ ) and one parafoveally presented ( $n + 1$ ). Foveal stimuli were displayed from  $0.9^\circ$  left of the fixation control (two vertically aligned bars, see Fig. 1) to  $1.35^\circ$  to the right of the fixation control (i.e., the participant's fixation was slightly left of the center of the foveal word; see Fig. 1). Parafoveal stimuli were presented from  $1.8^\circ$  to  $4.1^\circ$  to the right of the fixation control (total width of  $5^\circ$  of visual angle). The four possible combinations of stimuli were: WW - word ( $n$ ) word ( $n + 1$ ); WP - word ( $n$ ) pseudoword ( $n + 1$ ); PW - pseudoword ( $n$ ) word ( $n + 1$ ); PP - pseudoword ( $n$ ) pseudoword ( $n + 1$ ). Words were extracted from the CELEX database [66]. Pseudowords were generated using the Wuggy software [67]. All stimuli were 5 letters in length and matched on various lexical and sublexical characteristics (see Table 1). Bigrams are the pairs of consecutive letters of a word (e.g., *wo*, *or* and *rd* in *word*). The average bigram frequency is the log-transformed mean of the frequencies of each bigram with regard to the number of occurrences of the bigram in all the words of the CELEX database. The first bigram frequency is the log-transformed number of occurrences with which a particular bigram occurs in the initial position of the words in the CELEX database. Levenshtein's distance is the mean number of insertions, omissions and substitutions of letters which are required to transform a word in its 20 closest neighbors.

#### 1.1.5. Experimental procedure

Each trial sequence started with the stimuli being presented in a degraded format. Degraded stimuli had 50% of the pixels displaced and were completely unreadable (see Fig. 1). The degraded stimuli allowed participants to correctly pre-allocate attentional resources towards

**Table 1**

. Means (and standard deviations) of the item characteristics. The column names denote the condition; Ww, for example, refers to the words in the word-word condition and wP refers to the pseudowords in the word-pseudoword condition. All reported values for word and bigram frequency are log-transformed. F values represent separate ANOVAs for each characteristic.

	Ww	wW	Wp	pW	wP	Pw	Pp	pP	F
Frequency	1.71(.47)	1.71(.67)	1.71(.47)	1.71(.68)	–	–	–	–	< 1
First Bigr. <sup>a</sup>	2.50(.35)	2.52(.37)	2.50(.36)	2.51 (.36)	2.50(.36)	2.50(.35)	2.50(.35)	2.50(.35)	< 1
Avg Bigr. <sup>b</sup>	3.97(.18)	3.97(.18)	3.97(.18)	3.97(.18)	3.98(.2)	3.97(.2)	3.97(.2)	3.97(.2)	< 1
Levenshtein Distance	1.82(.25)	1.82(.14)	1.82(.26)	1.82(.13)	1.84(.27)	1.86(.27)	1.86(.27)	1.85(.27)	2.7

Note. <sup>a</sup> First bigram frequency. <sup>b</sup> Average bigram frequency.

foveal and parafoveal positions of the visual span. Two vertical lines indicated a  $1^\circ$  visual area where a fixation duration of minimum 200 ms triggered stimulus appearance in the undegraded format. This ensured that the position of the eye fixation at the moment of stimulus appearance would be between the second and the third letter of the foveally presented stimuli - illustrated by the green box (not visible to the participant) in Fig. 1.

Stimuli remained on the screen in an undegraded format for 180 ms and were followed by a 2000 ms blank screen during which the responses via button press were recorded. A blank screen followed the participants' response for a random inter-trial interval of 1100–1250 ms. Participants were instructed to press a green button whenever a word appeared on the screen, independently whether it was in the foveal or the parafoveal position (conditions: WW, WP, PW). Consequently, a red button press was required only in the case of two simultaneously presented pseudowords (condition PP). A visual (a green or red cross) feedback, corresponding to a correct and an incorrect response respectively, was given at the end of each trial. Each experimental session began with 40 training trials and was divided into four runs of 100 trials each (about 8 min per run). The overall experiment lasted about 35 min. Participants were randomly assigned to one of the two stimulation protocols (left and right IPS stimulation – 20 participants per group). Each participant was tested twice: one session with active cathodal stimulation and one session with sham stimulation. The order of the sessions was counterbalanced across participants in a double-blinded procedure. A minimum interval of 24 h and a maximum interval of one week were kept between the two testing sessions.

#### 1.1.6. Accuracy rate and reaction time analysis

For each participant, we excluded all trials in which reaction times (RTs) were shorter than 150 ms or three standard deviations above or below the individual mean ( $\sim 2\%$  of the data). All RTs were log-transformed for the analyses. The accuracy rates indicate the mean percent of correct responses for each condition. Data were analyzed using a repeated measures ANOVA having as between participants factor the stimulated Hemisphere (left, right) and as within participants factors Stimulation (active, sham) and Condition (WW, WP, PW, PP). Post-hoc contrasts corrected for multiple comparisons (false discovery rate [68];) followed significant main effects for Condition or significant two-way (Stimulation \* Condition) and three-way interactions (Hemisphere \* Stimulation \* Condition). Data were analyzed with the package *ez* [69] in R (R Core Team, 2013).

#### 1.2. fMRI results

fMRI materials and methods are detailed in the supplementary material. A conjunction analysis (i.e., all conditions > baseline, see Fig. 2) evidenced activation in a network of regions commonly observed during visual word recognition (see [62–67] for reviews). Of particular relevance for the present study was the dorsal brain activation. Based on the existing literature, we expected that attention reallocation processes occurring during parafoveal preprocessing would induce brain activation in parietal regions. In line with our predictions,

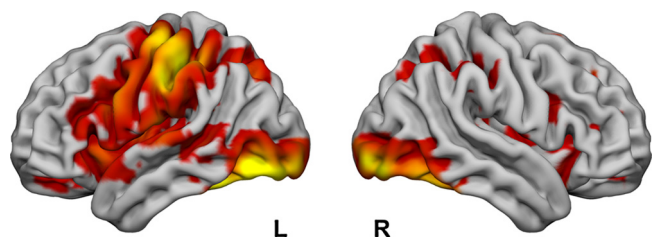


Fig. 2. Contrast of interest. Surface rendering of the contrast all conditions > baseline. L, left, R, right.

the conjunction analysis evidenced a significant cluster of activation in the bilateral inferior parietal cortex centered in and around the intra-parietal sulcus (IPS; Left IPS,  $x = -24, y = -61, z = 43$ ; Right IPS,  $x = 27, y = -61, z = 40$ ). It is important to note, however, that several aspects of foveal and parafoveal word reading might contribute to the observed parietal activation pattern. Therefore, the present findings must be interpreted with caution.

### 1.3. tDCS results

The overall mean accuracy rate was 75.3% correct responses ( $SD = 21.2\%$ ). Accuracy rates and reaction times (RTs) separated for participant groups (left IPS, right IPS) and stimulation sessions (real, sham) are depicted in Fig. 3A. The ANOVA evidenced a significant main effect of Condition in both accuracy rates [ $F(3,114) = 459.78, p < 0.001$ ] and RTs [ $F(3,114) = 510.94, p < 0.001$ ] but no other main effects or interactions [ $F_s < 1, p_s > .1$ ].

In addition, the data were examined using Bayesian statistics and estimating a Bayes factor [70] comparing the fit of the data under the null hypothesis and alternative hypothesis. We conducted two Bayesian repeated-measures ANOVAs (in JASP, <https://jasp-stats.org/>), one for accuracy rates and one for RTs. The design was identical to that of the parametric repeated measure ANOVA.

In the accuracy rates Bayesian ANOVA, the Bayes factors ( $BF_{10}$ ) for the main effects of Condition, Stimulation and Hemisphere were

$BF_{10} = 7.06e + 112, BF_{10} = .12$  and  $BF_{10} = .23$ , respectively. The Bayes factors for the interactions Condition \* Stimulation and Hemisphere \* Condition \* Stimulation were  $BF_{10} = .04$  and  $BF_{10} = .22$ , respectively. In the reaction times Bayesian ANOVA the Bayes factors ( $BF_{10}$ ) for the main effects of Condition, Stimulation and Hemisphere were  $BF_{10} = 2.64e + 83, BF_{10} = .45$  and  $BF_{10} = .37$ , respectively. The Bayes factors for the interactions Condition \* Stimulation and Hemisphere \* Condition \* Stimulation were  $BF_{10} = .04$  and  $BF_{10} = .09$ , respectively.

At this point it is important to consider that when a Bayes factor is smaller than 0.33, the  $H_0$  is supported [71,72]. This was always the case in the interactions Condition \* Stimulation and Hemisphere \* Condition \* Stimulation, thus indicating that the data are more likely under the null hypothesis (i.e., no effects of stimulation on both accuracy rates and reaction times) than under the alternative hypothesis. Crucially, in the reaction times analysis a  $BF_{10}$  of 0.45 and 0.37 for Stimulation and Hemisphere, respectively, does neither provide strong support for the alternative nor for the null hypothesis.

For the purpose of the present study it is important to emphasize that behavioral results during cathodal tDCS stimulation and during sham stimulation did not significantly differ from each other. This null-result was observed for both stimulation sites (i.e., left IPS and right IPS). Therefore, we aggregated both measures across participant groups and stimulation sessions (see Fig. 3B). Post-hoc  $t$ -tests revealed significant differences across all conditions [ $p_s < .05$ ] for accuracy rates as well as for RTs.

In the WW condition, foveally presented words were easy to recognize, reflected in high accuracy rates (WW -  $M = 93.7\%$ ,  $SD = 2.6\%$ ) and short RTs (WW -  $M = 422$  ms,  $SD = 157$  ms). Notably, however, foveal word recognition was impaired when a pseudoword was parafoveally presented (i.e., WP condition), thus reflected in lower accuracy rates (WP -  $M = 89.9\%$ ,  $SD = 4.1\%$ ) and longer reaction times (WP -  $M = 427$  ms,  $SD = 168$  ms). Parafoveally presented words were harder to recognize and led to a lower number of correct responses (PW -  $M = 48.5\%$ ,  $SD = 6.8\%$ ) and longer RTs ( $M = 672$  ms,  $SD = 292$  ms). Last, in the PP condition participants had a mean accuracy rate of 69.2% ( $SD = 4.6\%$ ) and mean RTs of 767 ms ( $SD = 252$  ms).

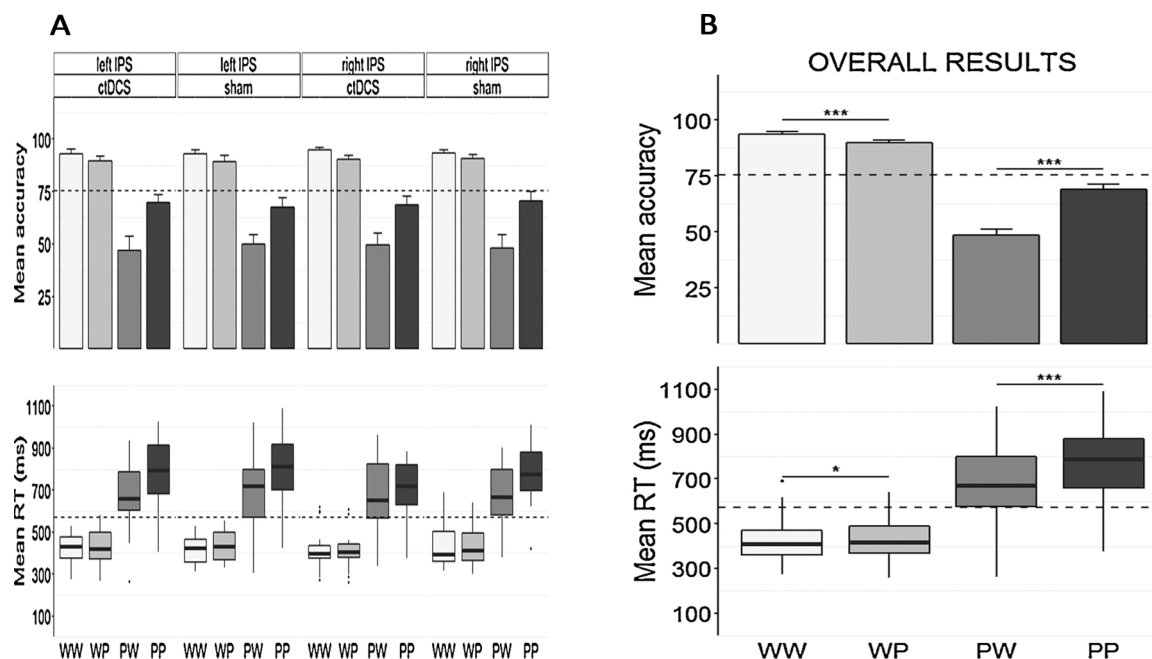


Fig. 3. tDCS results. (A) Mean accuracy rate (percent correct) and reaction times (RTs) in the different stimulation protocols. (B) Overall results of mean accuracy rate and RTs aggregated across stimulation protocols. Error bars represent 95% confidence intervals. Significant differences between conditions are marked with asterisks: \*\*\*  $p < 0.001, ** p < 0.01, * p < 0.05$ . Dashed lines represent the average accuracy rate (upper panel) and reaction time (lower panel) across conditions and stimulation protocols. WW, word word; WP, word pseudoword; PW, pseudoword word; PP, pseudoword pseudoword.



## 2. Discussion

The objective of the present study was to investigate neural correlates of attention deployment in parafoveal preprocessing. To this end we used transcranial direct current stimulation (tDCS) in order to directly assess the causal role of regions along the dorsal attentional system during parafoveal preprocessing. The main finding was that posterior parietal tDCS did not affect task performance.

### 2.1. tDCS of the PPC

The overall pattern of results was in line with our predictions, with higher accuracy rates and faster reaction times in conditions with foveally presented words (condition WW and WP) as compared to foveally presented pseudowords (conditions PW and PP). Importantly, in the conditions with foveally presented words when a pseudoword was parafoveally presented we observed a deteriorated behavioral performance (i.e., lower accuracy rates and higher reaction times). Such an effect is known as parafoveal on foveal effect (PoF). During the PoF effect, properties of the string to the right of the fixation influence processing of the currently fixated word [73]. Parafoveal on foveal effects, however, are a highly controversial topic in the eye tracking literature. Although a number of studies reported evidence for lexical-semantic processing of parafoveal words [74–83] some authors remain more cautious and assume only orthographic processing of parafoveal stimuli (see [1,84,85]).

Results from the current study support the former view, with lexical properties of parafoveal stimuli affecting foveal processing (see also). Interestingly, however, no such an effect was observed in the conditions with foveally presented pseudowords. In the PW condition, performance was at chance level, indicating that participants were not able to recognize parafoveally presented words. Accordingly, we interpreted the relatively high accuracy rate (69.2%) observed in the PP condition as the result of response strategies employed by the participants (they were more inclined towards a “no” response when unable to correctly identify parafoveally presented stimuli) rather than participants being able to fully process parafoveally presented (pseudo)words. What appears from the above reported findings is that the difficulty of the currently fixated stimulus affects the amount of information that can be parafoveally processed. This observation is in line with the foveal load hypothesis [86].

One of the main concerns raised by advocates of a more constrained view of PoF effects (i.e., only sublexical PoF) is that studies reporting lexical and semantic PoF effects adopted tasks which can hardly generalize to natural reading. Although recent studies reported evidence that flanker tasks provide an effective analogy to natural reading conditions [87] it will be important to replicate the present findings under more ecologically valid settings.

As far as it concerns effects of current stimulation, we expected cathodal stimulation over the left or right IPS to impair processing of parafoveally presented letter strings. Against our expectations, cathodal tDCS did not influence the overall behavioral performance. The behavioral findings were virtually identical in the stimulation conditions and the sham conditions and this was the case for both, the left and the right, IPS stimulation.

This null-result is in contrast with previous experiments reporting effects of parietal current stimulation during attention-related tasks. For example, Moos et al. (2012) [58] reported facilitatory effects in the top-down control of attention after 2 mA cathodal stimulation over the right IPS but not after 1 mA current stimulation for the same stimulation site. Ball et al. (2013) [54] used cathodal and anodal current stimulation to investigate orienting of spatial attention during a visual search task and reported inhibitory effects of 1 mA cathodal current stimulation on response times, but no effect on accuracy rates. Using similar tDCS parameters, Sparing et al. (2009) [61] observed that the effect of tDCS on the performance during a visuospatial task was dependent on the

hemisphere stimulated as well as the polarity (cathodal vs. anodal). Notably, the effect of polarity was also observed when stimulation was applied to the PPC. Filmer et al. (2015) [57] reported inhibitory effects of 1 mA anodal current stimulation on the contralateral hemisphere in a detection task of unilaterally presented competing stimuli. If, however, stimuli were presented bilaterally, both cathodal and anodal stimulation had inhibitory effects. Conversely, anodal stimulation over the PPC resulted in facilitatory effects in several other studies [14,56,60,61]. Furthermore, Bardi et al., (2013) [55] reported opposite effects of current stimulation depending on subtle differences in attentional control demands. To summarize, tDCS stimulation of the PPC during attention related task led to thoroughly diverse findings. It could be argued that adjustable parameters (i.e., current density, direction of the current flow, stimulation duration and electrode position) could explain the null-effects in the present study. In the following, we will address each of these parameters individually.

In the literature, the current density delivered varied between 0.029 mA/cm<sup>2</sup> and 0.08 mA/cm<sup>2</sup> [47]. Current density was often chosen following the rationale that higher current densities would correspond to enhanced stimulation effects. Accordingly, one might conclude that in the present study, a current density of 0.043 mA/cm<sup>2</sup> might not have been sufficiently strong to effectively modulate cortical excitability in the brain areas located in the depth of the IPS. Linear effects of current density, however, were demonstrated only for current densities up to 0.029 mA/cm<sup>2</sup> (i.e., current strengths up to 1 mA, which was varied, with 35 cm<sup>2</sup> fixed-size electrodes [48]). Conversely, increasing current density from 0.029 mA/cm<sup>2</sup> to 0.057 mA/cm<sup>2</sup> did not induce a linear increase in motor evoked potential amplitudes, but instead a change in the direction of effects with 0.029 mA/cm<sup>2</sup> cathodal tDCS having inhibitory effects and 0.057 mA/cm<sup>2</sup> cathodal tDCS having excitatory effects [88]. Finally, recent studies on human corpses demonstrated that approximately three quarters of scalp-applied currents were lost due to skin and skull resistance [88]. Moreover, Vöröslakos et al., (2018) [89] evidenced that only currents larger than 4–6 mA can affect neuronal firing. Importantly, currents of 4–6 mA are considerably higher than accepted guidelines for tDCS, where current intensities generally do not exceed 2 mA [47]. Vöröslakos et al.,'s (2018) [89] as well as others [90–92] results call for an update of standardized guidelines of this field of research.

Another important factor in determining the effect of tDCS is the direction of the current flow. As described by Jacobson, Koslowsky and Lavidor (2012) [93], the commonly accepted dichotomy of anodal and cathodal stimulation (inducing excitatory and inhibitory effects, respectively) may well apply to stimulation of the motor cortex, but is rather arbitrary in studies targeting higher-order cognitive domains. In the present study, cathodal stimulation did not improve or deteriorate task performance, hence we cannot draw conclusions concerning the direction of the effects of cathodal current stimulation on parafoveal preprocessing. Instead, what has to be noted is that effects of stimulation intensity and current polarity are not independent from other adjustable parameters (i.e., stimulation duration). Besides non-linear effects of current density, Batsikadze et al., (2013) [88] observed unsystematic after-effects following stimulation. Specifically, with a 20 min, 2 mA stimulation the authors reported a significant increase in motor evoked potential (MEP) amplitudes after 60 and 90 min of anodal stimulation and after 90 and 120 min of cathodal stimulation. Notably, replicating the same experiment with 1 mA cathodal current stimulation showed a significant decrease of MEP amplitudes immediately after and up to 120 min after stimulation. As far as it concerns the present study, behavioral measures of accuracy and reaction times were recorded on-line, while tDCS was ongoing. As demonstrated by Batsikadze et al., (2013) [88], however, effects of high densities (> 0.028 mA/cm<sup>2</sup>) and long duration (> 7 min) stimulation protocols might not emerge until 90 min after stimulation. In line with recent results [91,93,94] the present results seem to support the idea that single session cathodal tDCS might not be a well suited protocol to

induce observable changes in behavior. Additionally, it is important to note that missing tDCS findings at the behavioral level do not necessarily have to be interpreted as unaltered brain activity. As demonstrated by Hampstead, Brown and Hartley (2014) [95], tDCS induced polarity dependent changes in both the magnitude of the BOLD signal and effective connectivity without affecting the behavioral performance.

In sum, it could be argued that single session cathodal tDCS is not a reliable tool to draw causal inferences between brain activity and behavior – at least not in our task and in our healthy adult participants. This interpretation would conform the growing skepticisms regarding single session tDCS protocols [91,96] as well as the here described inconsistencies and the seemingly arbitrariness of findings in the literature. Although these issues cannot be fully addressed by the present work, current density models may help shed some light on the here reported null-result.

Using a simulation software for non-invasive brain stimulation (SimNIBS 2.1 [97]), we modeled current density distribution as a function of current strength (1.5 mA, 2 mA), electrode position (contralateral supraorbital montage vs bilateral montage) and cathodal electrode size (16 cm<sup>2</sup> vs. 35 cm<sup>2</sup>) (see Supplementary materials). Current density using the present study's contralateral supraorbital montage and the 35 cm<sup>2</sup> cathodal electrode patch, spread across multiple areas encompassing parietal cortex, superior parietal lobule, angular gyrus, occipito-temporal cortex as well as postcentral and supramarginal gyrus. Increasing current density to 2 mA only marginally affected the distribution of the effect, with similar areas being stimulated albeit with an overall increased current density. In the model simulating a bilateral montage (1.5 mA, 35 cm<sup>2</sup> electrode patch) we observed increased current density in the superior parietal cortex and decreased current density in all other areas. Last, smaller electrode patches (1.5 mA, 16 cm<sup>2</sup>) produced an overall more focal current distribution in and around the posterior parietal cortex.

Many factors contribute to the current density distribution, thus the present simulations must be interpreted with caution. Current densities of 1.5 mA and 2 mA using a 35 cm<sup>2</sup> electrode patch distributed across several areas (including the IPS). This was potentially detrimental to the aims of the present experiment. Using identical stimulation parameters and a bilateral montage we observed increased current densities around superior parietal areas but decreased stimulation of the posterior parietal cortex. Last, using smaller electrode patches (16 cm<sup>2</sup>) but the same montage adopted by the present study, current density increased in and around the posterior parietal cortex. Current modeling seems to indicate that smaller electrode patches might increase the likelihood of only relevant cortical neurons being stimulated, thus implicating an important avenue for future investigations [98].

### 3. Conclusions

In order to assess the neural underpinnings of parafoveal preprocessing during reading we used non-invasive brain stimulation by means of cathodal tDCS. The stimulation was targeted at the intraparietal sulcus with its putative role in attention reallocation processes during parafoveal preprocessing. Despite following well standardized experimental protocols, cathodal tDCS of the IPS did not modulate task performance. Future research should further specify the individual contributions of regions within the frontoparietal network in relation to parafoveal preprocessing. Replicating the present experiment with different non-invasive brain stimulation techniques (e.g., TMS) or stimulation parameters could shed light on both the here reported missing tDCS effects and the role of the IPS in attention deployment in parafoveal preprocessing during reading. The investigation of parafoveal preprocessing during ecologically valid reading situations remains an important avenue of research for future studies.

### Author contributions

Conceptualized and designed the experiment (LV, SH, FH, FR); acquired the data (LV, FR), analyzed the data (LV, FR); wrote the article (LV, SH, FH, FR). All authors have approved the final version of the article and agree to be accountable for all aspects of this work.

### Conflict of interest statement

The authors declare that the research was conducted in the absence of any commercial or financial relationship that can be construed as a potential conflict of interest.

### Acknowledgments

This work was supported by the Austrian Science Fund (FWF P 25799).

### Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:<https://doi.org/10.1016/j.neulet.2019.05.003>.

### References

- [1] E. Schotter, B. Angele, K. Rayner, Parafoveal processing in reading, *Atten. Percept. Psychophys.* 74 (1) (2012) 5–35, <https://doi.org/10.3758/s1314-011-0219-2>.
- [2] K. Rayner, X. Li, A. Pollatsek, Extending the E-Z reader model of eye movement control to chinese readers, *Cognit. Sci.* 31 (6) (2007) 1021–1033.
- [3] E.D. Reichle, S.P. Liversedge, A. Pollatsek, K. Rayner, Encoding multiple words simultaneously in reading is implausible, *Trends Cogn. Sci.* 13 (3) (2009) 115–119.
- [4] E.D. Reichle, A. Pollatsek, D.L. Fisher, K. Rayner, Toward a model of eye movement control in reading, *Psychol. Rev.* 105 (1) (1998) 125.
- [5] E.D. Reichle, A. Pollatsek, K. Rayner, E-Z reader: a cognitive-control, serial-attention model of eye-movement behavior during reading, *Cognitive Systems Res.* 7 (1) (2006) 4–22.
- [6] E.D. Reichle, A. Pollatsek, K. Rayner, Modeling the effects of lexical ambiguity on eye movements during reading, *Eye Movements: A Window Mind Brain* (2007) 271–292.
- [7] E.D. Reichle, T. Warren, K. McConnell, Using EZ reader to model the effects of higher level language processing on eye movements during reading, *Psychonomic Bulletin & Rev.* 16 (1) (2009) 1–21.
- [8] R. Engbert, A. Longtin, R. Kliegl, A dynamical model of saccade generation in reading based on spatially distributed lexical processing, *Vision Res.* 42 (5) (2002) 621–636.
- [9] R. Engbert, A. Nuthmann, Em. Richter, R. Kliegl, SWIFT: a dynamical model of saccade generation during reading, *Psychol. Rev.* 112 (4) (2005) 777–813, <https://doi.org/10.1037/0033-295X.112.4.777>.
- [10] W. Braet, G. Humphreys, The "Special effect" of case mixing on word identification: neuropsychological and transcranial magnetic stimulation studies dissociating case mixing from contrast reduction, *J. Cognit. Neurosci.* 18 (10) (2006) 1666–1675.
- [11] W. Braet, G. Humphreys, A selective effect of parietal damage on letter identification in mixed case words, *Neuropsychologia* 45 (10) (2007) 2226–2233, <https://doi.org/10.1016/j.neuropsychologia.2007.02.016>.
- [12] L. Cohen, S. Dehaene, F. Vinckier, A. Jobert, A. Montavont, Reading normal and degraded words: contribution of the dorsal and ventral visual pathways, *Neuroimage* 40 (1) (2008) 353–366, <https://doi.org/10.1016/j.neuroimage.2007.11.036>.
- [13] F. Vinckier, L. Naccache, C. Papeix, J. Forget, V. Hahn-Barma, S. Dehaene, L. Cohen, "What" and "where" in word reading: ventral coding of written words revealed by parietal atrophy, *J. Cognit. Neurosci.* 18 (12) (2006) 1998–2012, <https://doi.org/10.1162/jocn.2006.18.12.1998>.
- [14] T. Minamoto, M. Azuma, M. Osaka, K. Yaoi, N. Osaka, A. Ashizuka, T. Mima, H. Fukuyama, The anodal tDCS over the left posterior parietal cortex enhances attention toward a focus word in a sentence, *Frontiers Hum. Neuroscience* 8 (2014), <https://doi.org/10.3389/fnhum.2014.00992>.
- [15] E. Schotter, E. Reichle, K. Rayner, Rethinking parafoveal processing in reading: serial-attention models can explain semantic preview benefit and N+2 preview effects, *Vis. Cognition* 22 (3-4) (2014) 309–333, <https://doi.org/10.1080/13506285.2013.873508>.
- [16] T. Baccino, Y. Manunta, Eye-fixation-related potentials: insight into parafoveal processing, *J. Psychophysiol.* 19 (3) (2005) 204–215.
- [17] H.A. Barber, S. Ben-Zvi, S. Bentin, M. Kutas, Parafoveal perception during sentence reading? An ERP paradigm using rapid serial visual presentation (RSVP) with flankers, *Psychophysiology* 48 (4) (2011) 523–531.
- [18] H.A. Barber, N. Donamayor, M. Kutas, T. Munte, Parafoveal N400 effect during sentence reading, *Neurosci. Lett.* 479 (2) (2010) 152–156, <https://doi.org/10.1016/j.neulet.2010.05.053> [doi].

- [19] H.A. Barber, M. van der Meij, M. Kutas, An electrophysiological analysis of contextual and temporal constraints on parafoveal word processing, *Psychophysiology* 50 (1) (2013) 48–59, <https://doi.org/10.1111/j.1469-8986.2012.01489.x> [doi].
- [20] P. López-Peréz, J. Dampurá, J. Hernández-Cabrera, H. Barber, Semantic parafoveal-on-foveal effects and preview benefits in reading: evidence from fixation related potentials, *Brain Lang.* 162 (2016) 29–34.
- [21] W. Becker, R. Jürgens, An analysis of the saccadic system by means of double step stimuli, *Vision Res.* 19 (9) (1979) 967–983.
- [22] K. Rayner, M.L. Slowiaczek, C. Clifton, J.H. Bertera, Latency of sequential eye movements: implications for reading, *J. Exp. Psychol. Hum. Percept. Perform.* 9 (6) (1983) 912.
- [23] S.C. Sereno, K. Rayner, M.I. Posner, Establishing a time-line of word recognition: evidence from eye movements and event-related potentials, *Neuroreport* 9 (10) (1998) 2195–2200.
- [24] S.C. Sereno, K. Rayner, Measuring word recognition in reading: eye movements and event-related potentials, *Trends Cogn. Sci.* 7 (11) (2003) 489–493.
- [25] M. Carreiras, B.C. Armstrong, M. Perea, R. Frost, The what, when, where, and how of visual word recognition, *Trends Cogn. Sci.* 18 (2) (2014) 90–98.
- [26] C. Pernet, J. Uusvuori, R. Salmelin, Parafoveal-on-foveal and foveal word priming are different processes: behavioral and neurophysiological evidence, *NeuroImage* 38 (2) (2007) 321–330.
- [27] N. Dare, R. Shillcock, Serial and parallel processing in reading: investigating the effects of parafoveal orthographic information on nonisolated word recognition, *Q. J. Exp. Psychol. (Hove)* 66 (3) (2013) 487–504.
- [28] E.D. Reichle, K. Rayner, A. Pollatsek, The EZ reader model of eye-movement control in reading: comparisons to other models, *Behav. Brain Sci.* 26 (4) (2003) 445–476.
- [29] M. Corbetta, J.M. Kincade, J. Ollinger, M. McAvoy, L. Gordon, Voluntary orienting is dissociated from target detection in human posterior parietal cortex, *Nat. Neurosci.* 3 (3) (2000) 292–297.
- [30] M. Corbetta, G. Shulman, Control of goal-directed and stimulus-driven attention in the brain, *Nat. Reviews: Neuroscience* 3 (2002) 201–214, <https://doi.org/10.1038/nrn755>.
- [31] A. Ikkai, C. Curtis, Cortical activity time locked to the shift and maintenance of spatial attention, *Cereb. Cortex* 18 (6) (2008) 1384–1394, <https://doi.org/10.1093/cercor/bhm171>.
- [32] P. Thakral, S. Slotnick, The role of parietal cortex during sustained visual spatial attention, *Brain Res.* 1302 (2009) 157–166, <https://doi.org/10.1016/j.brainres.2009.09.031>.
- [33] R. Vandenberghe, S. Geeraerts, P. Molenberghs, C. Lafosse, M. Vandenbulcke, K. Peeters, R. Peeters, P. Van Hecke, G. Orban, Attentional responses to unattended stimuli in human parietal cortex, *Brain: J. Neurol.* 128 (2005) 2843–2857, <https://doi.org/10.1093/brain/awh522>.
- [34] J. Bisley, M. Goldberg, Attention, intention, and priority in the parietal lobe, *Annu Rev. Neurosci.* 33 (2010) 1–21, <https://doi.org/10.1146/annurev-neuro-060909-152823>.
- [35] M. Corbetta, J.M. Kincade, G. Shulman, Neural systems for visual orienting and their relationships to spatial working memory, *J. Cognit. Neurosci.* 14 (3) (2002) 508–523.
- [36] J. Gottlieb, From thought to action: the parietal cortex as a Bridge between perception, action, and cognition, *Neuron* 53 (1) (2007) 9–16, <https://doi.org/10.1016/j.neuron.2006.12.009>.
- [37] P. Molenberghs, M. Mesulam, R. Peeters, R. Vandenberghe, Remapping attentional priorities: differential contribution of superior parietal lobule and intraparietal sulcus, *Cereb. Cortex* 17 (11) (2007) 2703–2712, <https://doi.org/10.1093/cercor/bhl179>.
- [38] T. Silk, M. Bellgrove, P. Wrafter, J. Mattingley, R. Cunnington, Spatial working memory and spatial attention rely on common neural processes in the intraparietal sulcus, *Neuroimage* 53 (2) (2010) 718–724, <https://doi.org/10.1016/j.neuroimage.2010.06.068>.
- [39] M. Behrmann, J. Geng, S. Shomstein, Parietal cortex and attention, *Curr. Opin. Neurobiol.* 14 (2) (2004) 212–217, <https://doi.org/10.1016/j.conb.2004.03.012>.
- [40] J. Gottlieb, P. Balan, Attention as a decision in information space, *Trends Cogn. Sci.* 14 (6) (2010) 240–248, <https://doi.org/10.1016/j.tics.2010.03.001>.
- [41] C. Constantinidis, M.A. Steinmetz, Neuronal activity in posterior parietal area 7a during the delay periods of a spatial memory task, *J. Neurophysiol.* 76 (2) (1996) 1352–1355.
- [42] L. Pessoa, M. McKenna, E. Gutierrez, L.G. Ungerleider, Neural processing of emotional faces requires attention, *Proc. Natl. Acad. Sci. U. S. A.* 99 (17) (2002) 11458–11463.
- [43] J. Todd, R. Marois, Capacity limit of visual short-term memory in human posterior parietal cortex, *Nature* 428 (6984) (2004) 751–754, <https://doi.org/10.1038/nature02466>.
- [44] J. Bisley, M. Goldberg, Neuronal activity in the lateral intraparietal Area and spatial attention, *Science* 299 (5603) (2003) 81–86.
- [45] S. Yantis, J. Schwarzbach, J. Serences, R. Carlson, M. Steinmetz, J. Pekar, S. Courtney, Transient neural activity in human parietal cortex during spatial attention shifts, *Nat. Neurosci.* 5 (10) (2002) 995–1002, <https://doi.org/10.1038/nn921>.
- [46] J. Silvano, A. Pascual-Leone, Why the assessment of causality in brain-behavior relations requires brain stimulation, *J. Cognit. Neurosci.* 24 (4) (2012) 775–777.
- [47] F. Fregni, A. Pascual-Leone, Technology insight: noninvasive brain stimulation in neurology—perspectives on the therapeutic potential of rTMS and tDCS, *Nat. Clin. Pract. Neurol.* 3 (7) (2007) 383–393.
- [48] M. Nitsche, L. Cohen, E. Wassermann, A. Priori, N. Lang, A. Antal, W. Paulus, F. Hummel, P. Boggio, F. Fregni, A. Pascual-Leone, Transcranial direct current stimulation: State of the art 2008, *Brain Stimulation* 1 (3) (2008) 206–223, <https://doi.org/10.1016/j.brs.2008.06.004>.
- [49] M. Nitsche, W. Paulus, Excitability changes induced in the human motor cortex by weak transcranial direct current stimulation, *The J. Physiology* 527 (3) (2000) 633–639, <https://doi.org/10.1111/j.1469-7793.2000.t01-1-00633.x>.
- [50] W. Paulus, Transcranial direct current stimulation (tDCS), *Suppl. Clin. Neurophysiol.* 56 (2003) 249–254.
- [51] R. Sparing, F. Mottaghy, Noninvasive brain stimulation with transcranial magnetic or direct current stimulation (TMS/tDCS) - from insights into human memory to therapy of its dysfunction, *Methods* 44 (4) (2008) 329–337, <https://doi.org/10.1016/j.yemeth.2007.02.001>.
- [52] E. Wassermann, J. Grafman, Recharging cognition with DC brain polarization, *Trends Cogn. Sci.* 9 (11) (2005) 503–505, <https://doi.org/10.1016/j.tics.2005.09.001>.
- [53] M. Nitsche, K. Fricke, U. Henschke, A. Schlitterlau, D. Liebetanz, N. Lang, S. Henning, F. Tergau, W. Paulus, Pharmacological modulation of cortical excitability shifts induced by transcranial direct current stimulation in humans, *The J. Physiology* 553 (1) (2003) 293–301, <https://doi.org/10.1113/jphysiol.2003.049916>.
- [54] M. Nitsche, W. Paulus, Sustained excitability elevations induced by transcranial DC motor cortex stimulation in humans, *Neurology* 57 (2001) 1899–1901.
- [55] K. Ball, A. Lane, D. Smith, A. Ellison, Site-dependent effects of tDCS uncover dissociations in the communication network underlying the processing of visual search, *Brain Stimulation* 6 (6) (2013) 959–965, <https://doi.org/10.1016/j.brs.2013.06.001>.
- [56] L. Bardí, R. Kanai, D. Mapelli, V. Walsh, Direct current stimulation (tDCS) reveals parietal asymmetry in local/global and salience-based selection, *Cortex* 49 (3) (2013) 850–860, <https://doi.org/10.1016/j.cortex.2012.04.016>.
- [57] N. Bolognini, F. Fregni, C. Casati, E. Olgati, G. Vallar, Brain polarization of parietal cortex augments training-induced improvement of visual exploratory and attentional skills, *Brain Res.* 1349 (2010) 76–89, <https://doi.org/10.1016/j.brainres.2010.06.053>.
- [58] H. Filmer, P. Dux, J. Mattingley, Dissociable effects of anodal and cathodal tDCS reveal distinct functional roles for right parietal cortex in the detection of single and competing stimuli, *Neuropsychologia* 74 (2015) 120–126, <https://doi.org/10.1016/j.neuropsychologia.2015.01.038>.
- [59] K. Moos, S. Vossel, R. Weidner, R. Sparing, G. Fink, Modulation of top-down control of visual attention by cathodal tDCS over right IPS, *The J. Neuroscience: Official J. the Society For Neuroscience* 32 (46) (2012) 16360–16368, <https://doi.org/10.1523/JNEUROSCI.6233-11.2012>.
- [60] J.M. Roe, M. Nesheim, N.C. Mathiesen, T. Moberget, D. Alnaes, M.H. Sneve, The effects of tDCS upon sustained visual attention are dependent on cognitive load, *Neuropsychologia* 80 (2016) 1–8.
- [61] L. Roy, R. Sparing, G. Fink, M. Hesse, Modulation of attention functions by anodal tDCS on right PPC, *Neuropsychologia* 74 (2015) 96–107, <https://doi.org/10.1016/j.neuropsychologia.2015.02.028>.
- [62] R. Sparing, M. Thimm, M. Hesse, J. Küst, H. Karbe, G. Fink, Bidirectional alterations of interhemispheric parietal balance by non-invasive cortical stimulation, *Brain* 132 (11) (2009) 3011–3020, <https://doi.org/10.1093/brain/awp154>.
- [63] A. Martin, M. Schurz, M. Kronbichler, F. Richlan, Reading in the brain of children and adults: a meta-analysis of 40 functional magnetic resonance imaging studies, *Hum. Brain. Mapp.* 36 (5) (2015) 1963–1981.
- [64] C.J. Price, A review and synthesis of the first 20years of PET and fMRI studies of heard speech, spoken language and reading, *Neuroimage* 62 (2) (2012) 816–847.
- [65] J.S.H. Taylor, K. Rastle, M.H. Davis, Can cognitive models explain brain activation during word and pseudoword reading? A Meta-Analysis 36 *Neuroimaging Stud.* (2013).
- [66] G. Jobard, F. Crivello, N. Tzourio-Mazoyer, Evaluation of the dual route theory of reading: a meta-analysis of 35 neuroimaging studies, *Neuroimage* 20 (2) (2003) 693–712.
- [67] R.H. Baayen, R. Piepenbrock, H.R. van, The {CELEX} Lexical Data Base on {CD-ROM}, (1993).
- [68] E. Keuleers, M. Brysbaert, Wuggy: a multilingual pseudoword generator, *Behav. Res. Methods* 42 (3) (2010) 627–633.
- [69] Y. Benjamini, Y. Hochberg, Controlling the false discovery rate: a practical and powerful approach to multiple testing, *J. the Royal Statistical Society. Ser. B (Methodological)* (1995) 289–300.
- [70] M.A. Lawrence, Ez: Easy analysis and visualization of factorial experiments, *Computer Softw. Man.]* (2011) (R Package Version 3.0-0).
- [71] E.J. Wagenmakers, A practical solution to the pervasive problems of p-values, *Psychonomic Bulletin & Rev.* 14 (5) (2007) 779–804.
- [72] A.E. Raftery, Bayesian model selection in social research, *Sociological Methodology* (1995) 111–163.
- [73] A.F. Jarosz, J. Wiley, What are the odds? A practical guide to computing and reporting bayes factors, *The J. Problem Solving* 7 (1) (2014) 2.
- [74] A. Kennedy, J. Pynte, S. Ducrot, Parafoveal-on-foveal interactions in word recognition, *The Q. J. Experimental Psychology Section A* 55 (4) (2002) 1307–1337.
- [75] J. Hyönä, R. Bertram, Do Frequency characteristics of nonfixated words influence the processing of fixated words during reading? *Eur. J. Cogn. Psychol.* 16 (1-2) (2004) 104–127.
- [76] A.W. Inhoff, R. Radach, M. Starr, S. Greenberg, Allocation of visuo-spatial attention and saccade programming during reading, *Reading as a Perceptual Process*, North-Holland, 2000, pp. 221–246.
- [77] A.W. Inhoff, M. Starr, K.L. Shindler, Is The processing of words during eye fixations in reading strictly serial? *Percept. & Psychophysics* 62 (7) (2000) 1474–1484.
- [78] A. Kennedy, The influence of parafoveal words on foveal inspection time: evidence for a processing trade-off, *Eye Guidance in Reading and Scene Perception*, Elsevier

- Science Ltd, 1998, pp. 149–179.
- [79] A. Kennedy, Parafoveal processing in word recognition, *The Q. J. Experimental Psychology Section A* 53 (2) (2000) 429–455.
- [80] W. Schroyens, F. Vitu, M. Brysbaert, G. d'Ydewalle, Eye movement control during reading: foveal load and parafoveal processing, *The Q. J. Experimental Psychology Section A* 52 (4) (1999) 1021–1046.
- [81] M. Starr, A. Inhoff, Attention allocation to the right and left of a fixated word: use of orthographic information from multiple words during reading, *Eur. J. Cogn. Psychol.* 16 (1-2) (2004) 203–225.
- [82] G. Underwood, A. Binns, S. Walker, Attentional demands on the processing of neighbouring words, *Reading as a Perceptual Process*, North-Holland, 2000, pp. 247–268.
- [83] F. Vitu, M. Brysbaert, D. Lancelin, A test of parafoveal-on-foveal effects with pairs of orthographically related words, *Eur. J. Cogn. Psychol.* 16 (1-2) (2004) 154–177.
- [84] K. Rayner, B. Juhasz, Eye movements in reading: Old questions and new directions, *Eur. J. Cogn. Psychol.* 16 (1-2) (2004) 340–352.
- [85] L. Vignali, S. Hawelka, F. Hutzler, F. Richlan, Processing of parafoveally presented words. An fMRI study, *Neuroimage* 184 (2019) 1–9.
- [86] J.M. Henderson, F. Ferreira, Effects of foveal processing difficulty on the perceptual span in reading: implications for attention and eye movement control, *J. Experimental Psychology: Learning, Mem., Cognition* 16 (3) (1990) 417.
- [87] J. Snell, M. Declerck, J. Grainger, Parallel semantic processing in reading revisited: effects of translation equivalents in bilingual readers, *Lang., Cognition Neuroscience* 33 (5) (2018) 563–574.
- [88] G. Batsikadze, V. Moliadze, W. Paulus, M.F. Kuo, M.A. Nitsche, Partially non-linear stimulation intensity-dependent effects of direct current stimulation on motor cortex excitability in humans, *The J. Physiology* 591 (7) (2013) 1987–2000.
- [89] M. Voroslakos, Y. Takeuchi, K. Brinyiczki, T. Zombori, A. Oliva, A. Fernandez-Ruiz, A. Berenyi, Direct effects of transcranial electric stimulation on brain circuits in rats and humans, *Nat. Commun.* 9 (1) (2018) 483-018-02928-3, <https://doi.org/10.1038/s41467-018-02928-3> [doi].
- [90] J.C. Horvath, J.D. Forte, O. Carter, Evidence that transcranial direct current stimulation (tDCS) generates little-to-no reliable neurophysiologic effect beyond MEP amplitude modulation in healthy human subjects: a systematic review, *Neuropsychologia* 66 (2015) 213–236, <https://doi.org/10.1016/j.neuropsychologia.2014.11.021> [doi].
- [91] J.C. Horvath, J.D. Forte, O. Carter, Quantitative review finds no evidence of cognitive effects in healthy populations from single-session transcranial direct current stimulation (tDCS), *Brain Stimulation* 8 (3) (2015) 535–550, <https://doi.org/10.1016/j.brs.2015.01.400> [doi].
- [92] J.C. Horvath, O. Carter, J.D. Forte, No Significant effect of transcranial direct current stimulation (tDCS) found on simple motor reaction time comparing 15 different stimulation protocols, *Neuropsychologia* 91 (2016) 544–552 S0028-3932(16)30354-2 [pii].
- [93] L. Jacobson, M. Koslowsky, M. Lavidor, tDCS polarity effects in motor and cognitive domains: a meta-analytical review, *Exp. Brain Res.* 216 (1) (2012) 1–10.
- [94] S.J. Westwood, A. Olson, R.C. Miall, R. Nappo, C. Romani, Limits to tDCS effects in language: failures to modulate word production in healthy participants with frontal or temporal tDCS, *Cortex* 86 (2017) 64–82.
- [95] B. Hampstead, G. Brown, J. Hartley, Transcranial direct current stimulation modulates activation and effective connectivity during spatial navigation, *Brain Stimulation* 7 (2) (2014) 314–324, <https://doi.org/10.1016/j.brs.2013.12.006>.
- [96] J. Horvath, O. Carter, J. Forte, Transcranial direct current stimulation: five important issues we aren't discussing (but probably should be), *Front. Syst. Neurosci.* 8 (2014) 2, <https://doi.org/10.3389/fnsys.2014.00002>.
- [97] A. Thielscher, A. Antunes, G.B. Saturnino, August). Field modeling for transcranial magnetic stimulation: a useful tool to understand the physiological effects of TMS? 2015 37th Annual International Conference of the IEEE Engineering in Medicine and Biology Society (EMBC) (2015) 222–225.
- [98] M.F. Villamar, P. Wivatvongvana, J. Patumanond, M. Bikson, D.Q. Truong, A. Datta, F. Fregni, Focal modulation of the primary motor cortex in fibromyalgia using 4 × 1-ring high-definition transcranial direct current stimulation (HD-tDCS): immediate and delayed analgesic effects of cathodal and anodal stimulation, *The J. Pain* 14 (4) (2013) 371–383.