Neuromodulation of Attention in Reading:

The Effect of Left Hemispheric Occipital-Parietal tACS on Reading Speed in Natural Reading

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Abstract

Attention plays an important role in reading; studies have shown that visuospatial attention affects word perception (Montani et al., 2014) preview processing (Henderson & Ferreira, 1990). In the present study, we attempted to manipulate the visuospatial attention with intent of affecting the reading performance showing a link between visuospatial attention and reading performance. Based on rightward alpha lateralisation in the previous reading studies (Kornrumpf et al., 2017), I posited that transcranial alternating current stimulation (tACS) over left occipito parietal cortex would negatively affect reading speed. We designed a single-blind within participant study where participants were asked to read sets of sentences while receiving non-invasive brain stimulation and having their eye movements measured by an eye-link tracker. Our balanced experimental design had three stimulation conditions (left, right and sham) and two different reading conditions (natural and window-paradigm reading). I hypothesised the left stimulation condition would negatively affect the reading speed, resulting in longer total reading times compared to right and sham conditions. In order to explain the longer reading time a mediator of increased regressions was proposed. A total of 18 participants were used in our analysis and repeated measures anova showed no significant differences between total reading times or frequencies of regressions across the three stimulation conditions. Theoretical implications and limitations of the current study are discussed in the final section.

Keywords: Visuospatial attention, tACS, Reading and attention, Regressive saccades

The Effect of Left Hemispheric Occipital-Parietal tACS on Reading Speed in Natural Reading

It seems clear that the reading capabilities across the population differ from individual to individual. It is less clear however why there are such differences and what are the underlying processes explaining them (Shaywitz & Shaywitz, 2008). At the turn of the century a popular assumption about reading was that it is an automatic process of generation of phonological codes which does not require too much, if any attention (Gronau & Frost, 1997; Johnston & Castles, 2003). This theorising was based on visual word recognition processes. However this view has changed with the advancement of neuroscientific methods which allow us for a better insight into cognitive processes. Natural reading is a multifaceted process with several components. It has been increasingly considered that attention plays an important role in reading, both developmentally and as a factor in the process itself (Shaywitz & Shaywitz, 2008). For example, Stern and Shalev (2012) show a positive correlation between sustained attention in reading and comprehension scores, which seems to support the suggestion that attention plays a role in the reading process. Additionally, Montani et al. (2014) posit that visuospatial attention plays a role in word perception acting in the reading process. Reading is a complex process and there are different kinds of attention playing a role in different stages of reading. One of these is visuospatial attention that can be involved both in word perception (Montani et al., 2014) and the parafoveal preview and processing (Henderson & Ferreira, 1990).

Reading is a process of visual processing of written patterns where cognitive processes guide our visual sensory processing. The acuity of reading is highest in *fovea* (center of fixation and 1° of visual area to any side of it) but it is suggested that we also process information from the *parafoveal* area (1°–5° from the fixation point), especially to the right of fixation (Rayner et al., 2016). To move the foveal area of acuity the eyes perform high velocity movements referred to as *saccades* and they as well as the duration of how long we stay centered on a word, i.e. fixated, are determined by cognitive processes and are not preprogrammed (Rayner & Reingold, 2014).

Researching this topic is interesting and important as it has potentially relevant implications to understanding the process of reading on a brain level and has possible applications in understanding reading difficulties. It can be complicated to study cognitive concepts on a brain level and talk about causation, however this becomes possible to an extent if we are able to manipulate and change some factors through stimulation. Grover et al. (2023) show that transcranial alternating current stimulation (tACS) has been successful in manipulating cognitive functions across a range of groups in population through manipulation of brain's neural oscillations of excitatory and inhibitory neural circuits.

There is a growing body of research with visuospatial tasks that apply brain stimulation and shows a successful manipulation using tACS on spatial attention in tasks of endogenous/top down attention (Schuhmann et al., 2019; Kemmerer et al., 2022; Kasten et al., 2020). It is believed that visuospatial attention plays an important role in reading, and this assumption may perhaps be tested using the tACS approach on a reading study to see whether we can affect reading performance by transcranial brain stimulation.

Alpha oscillations and attention

When groups of several thousand neurons go through stages of inhibitory and excitatory states this is manifested as a brain oscillation which can be measured by a device such as an electroencephalogram (EEG) (Hanslmayr et al. 2011). These brain oscillations can differ in their frequency, and frequency oscillations between 7 to 13 Hz are called alpha oscillations (Schuhmann et al., 2019). From here on when alpha oscillations will be mentioned this will refer to the middle value of 10Hz. Another thing that oscillations can differentiate in are amplitudes; they are determined by how many and how synchronised neurons in an area are (Hanslmayr et al., 2011). It has been proposed that decreased amplitudes of alpha are linked to cortical activation as a response to stimuli, while increased amplitudes are connected to inhibition of irrelevant or unattended stimuli in cognitive processes (Peylo et al., 2021). In the present study we are interested in the role of alpha oscillations in reading and we wish to study that by manipulating brain activity with non-invasive brain stimulation.

Transcranial Alternating Current Stimulation (tACS)

By attaching electrodes to the scalp and applying weak electrical currents it is possible to impose weak electric fields to the human brain that resemble those naturally present in our neural functioning; one method that does this is tACS (Johnson et al., 2020). Transcranial alternating current stimulation can allow us to manipulate the rhythmicity of brain oscillations in a non-invasive manner (Wischnewski et al., 2022). As mentioned, tACS is already being used by cognitive neuroscientists to manipulate and study different kinds of cognitive processes such as memory, attention and perception (Johnson et al., 2020).

In the present study we wish to extend this field by using tACS in a reading task while tracking eye movements to see whether stimulation can affect the reading performance. Wöstmann et al. (2018) conducted a study where they successfully showed that continuous transcranial stimulation at alpha frequency had an effect on auditory spatial attention in listening and recall task. More specifically, they found increased recall performance for unihemispheric ipsilateral stimulation and decreased performance when alpha stimulation was applied contralateral to presented stimuli. This is in line with previous findings in visuospatial attention studies. In an experimental EEG study Worden et al. (2000) found that amplitudes of alpha oscillations in occipital cortex increased ipsilateral to the areas of cued attention. In other words, the amplitudes of the alpha band were larger on the same side that was attended. However since visual stimuli is processed contralaterally this means that the alpha amplitudes were increased on the area that was “to-be-ignored”. Results that are consistent with this role of lateralisation of alpha have been found in visuospatial studies using tACS. Kemmerer et al. (2022) stimulated both left and right temporoparietal brain areas during a simple Posner cueing task and found significant effects of alpha tACS on endogenous attentional bias. More importantly, Kasten et al. (2020) found a significant effect of alpha tACS on endogenous spatial attention while stimulating occipito-parietal cortex. This implies a direct link between visual cognitive processes in occipital cortex and alpha oscillations, and at the same time suggests that these processes can be modulated with tACS. Interestingly, both of these studies (Kasten et al., 2020; Kemmerer et al. 2022) found the effect of modulating visuospatial attention and positively affecting the attentional bias to be stronger for stimulation of the left hemisphere. This is important for the present study as reading in the western world is a process where we focus our attention to the right. Applying what we know about alpha to reading, EEG studies find a rightward lateralisation, meaning the amplitudes of alpha are higher in the right hemisphere and lower in the left (Kornrumpf et al., 2017). This means that if we can influence alpha bands of the left hemisphere we can show an effect in reading behaviour through modulation of visuospatial attention.

Visuospatial Attention and Alpha Power in Reading

A process that is automatic is often understood as requiring little effort or attention, and if we see natural reading as a normal process then we may think it does not require much attention (Shaywitz & Shaywitz, 2008). However, whereas visual word recognition of one word could be seen as automatic, there are other parts of natural reading where attention plays a role. As previously explained, there has been much research showing that reading is not an automated process (e.g. Kornrumpf et al., 2017; Stern & Shalev, 2012; Jensen et al., 2021) and that visuospatial attention does indeed play a role in reading (Henderson & Ferreira, 1990; Montani et al., 2014).

As aforementioned, saccadic eye movements are not programmed but are determined by cognitive processes. Pan et al. (2023) reports findings of a magnetoencephalography (MEG) study, linking saccades were locked to the phase of alpha oscillations in reading, with the effect being stronger for lexically more frequent words. They argue for the importance of alpha power in natural reading, stating it is important for the visual informational flow through saccades. Kornrumpf et al. (2017) analysed EEG measurements in saccadic reading and reported a link between alpha lateralisation and attention deployment in reading. In this study they hypothesized that alpha power is correlated with preview information we receive from parafoveal area; they found an association between rightward lateralisation alpha power and fixation duration of the following word. This means that if the alpha amplitude is lower in the left hemisphere and the fixation duration of the next word is shorter we can infer from this an increased deployment of attention. This is relevant for the present study because if we can disrupt this naturally occurring rightward lateralization of alpha by using tACS on the left hemisphere, then we may perhaps interfere with this visuospatial attention deployment process making the reading performance worse.

Regressive Saccades in Reading

Another type of saccadic movements common (5% - 20%) in reading are regressions which are return movements to the prior portion of the text (Inhoff et al., 2019). Rayner (2009) suggests that these backwards movements are usually responses to reading difficulties but Inhoff et al. (2019) extend the view of regressions positing at least two kinds that differ in form and function. According to this view the larger regressions that go back a couple of words are largely due to word difficulties, while smaller regressions within a word or to the prior adjacent word are due to the oculomotor target error. The authors further suggest that regressions can serve to validate or update the representation of linguistic information; in the case of small regressions this can be if the previous word was not fully processed. For large regressions the main hypothesis is the “re-viewing for reprocessing” tied to a change in linguistic meaning of a word (Inhoff et al., 2019). However, there is an alternate hypothesis that suggests regressions are not targeted to a specific word but they benefit comprehension because of the additional time for processing (Mitchell et al., 2008). This alternative theory is consistent with the idea that larger regressions are connected to retrieval of information from working memory and general findings that link regressions to better comprehension of the text (Inhoff et al., 2019). If we assume that tACS alpha manipulations can negatively influence reading abilities and comprehension, then this can perhaps be compensated by increasing the number of regressions to retain the same level of comprehension.

Reading Difficulties and Visuospatial Attention

Stern and Shalev (2012) conducted a study on reading comprehension and report a significant correlation between reading comprehension and sustained attention. Tsal et al. (2005) suggests that some reading difficulties may arise from deficient ability to restrict the visual attention to the relevant area while inhibiting information from the irrelevant visual areas. While Tsal et al. puts this idea forward as an explanation for reading difficulties in ADHD individuals, the situation resembles the one we wish to achieve in our present experimental study. We wish to influence the amplitude of alpha oscillations in the left hemisphere and therefore disrupt the rightward lateralization naturally present in reading. If we are able to do so, we may aggravate visual attention by disrupting cortical activation of attending to stimuli. We assume that this will affect the fluency and comprehension of reading and we posit that the deficit in comprehension will be compensated by longer reading time. The mechanism that is proposed explains the shortfall of visual attention will require more processing which will be manifested by more regressions in order to maintain comprehension levels. Based on this theorising, we present the following experimental hypotheses.

Hypothesis 1. Left unihemispheric occipitoparietal tACS compared to right tACS and the sham-control condition will result in longer overall reading times across experimental conditions, when controlled for comprehension.

Hypothesis 2. The effect of longer reading times from Hypothesis 1 will be mediated by an increase in regression frequency for the left occipitoparietal tACS compared to right tACS and the sham-condition, when controlled for comprehension.

Method

Participants

A total of 20 participants were recruited either through the university practicum system or convenience sampling. After checking for quality of measurements and balancing, a total of 18 participants (13 female, 5 male) were selected as our dataset. All participants were university students (ages 19 - 29, M = 21.5 years, SD = 2.04). All participants were non-native English speakers and they began acquiring English between 4 and 11 years (M = 7.8 years, SD = 2.2). According to the administered questionnaire, most of the participants were right handed (17 right handed, 1 left handed) and all participants had normal or corrected vision. The study was approved by the local ethics committee and participants provided a written consent form after being informed about the study and before the start of participation. For their participation those eligible received course credits. An a priori power analysis was performed based on effect sizes of previous tACS studies on visuospatial attention. A power calculation (a paired t-test; effect size dz = .44; α error probability = .05; Power 1-β error probability = 0.8) based on a paired-t test showed that 34 participants would be required to show significant statistical differences.

Reading Material

We developed an experimental design where the participants were asked to read a corpus of sentences having their eye-movement tracked while receiving tACS in three blocks of conditions. For the reading task we selected 200 sentences from an existing corpus in (Frank et al., 2013), all of the sentences were only so long that they fit to be displayed as a single-line sentence on the monitor to allow for single-line eye-tracking. Single, unrelated sentences in the Frank et al., 2013 corpus cannot be connected into a coherent story. A representative example of a sentence is: "*Joseph walked into the office and removed his flat cap.*", followed by a question: "*Did Joseph walk out of the office?*". A set of 180 sentences were split into three blocks of 60 for three experimental conditions; the rest of the sentences (20) were used in a practice trial that preceded the first block. Half of the sentences were displayed normally as a regular sentence and the other half was displayed with a moving window that followed the gaze of the participant and limited the parafoveal preview in the reading. The moving window size was 4 letters to the left of the center of gaze and 5 to the right of the gaze and it was programmed so that it allowed regressive eye movements. The concealed sections of the sentence were displayed by the letter x but maintained the spaces between words. The window size was determined based on the existing literature on this paradigm (Rayner, 2014) in an attempt to control for preview benefit in the parafoveal areas.

Comprehension Check

Across the experiment a third of the sentences were followed by a yes or no question that the participants could answer with a click of the mouse. The questions were presented randomly so the participants could not predict when a question would be asked. The questions acted as a comprehension check, making sure the participants actually read the sentences. Some of the questions were taken from the Frank et al., 2013 corpus and some were additionally created by the research team. The questions were balanced so that the number of questions that were answered with yes was the same as the number of questions where the right answer was no.

Eye-Tracking and Sentence Presentation

As the participants were reading the sentence material their eye movements were tracked using a high-resolution eye tracker Eyelink 1000 Plus by SR Research from Canada (SR Research Ltd., 2024). Before the experiment, the eye tracker was calibrated using a series of small target circles which the participants were instructed to fixate on. After calibration, a validation was performed and only then would the experiment commence. The reading material was presented on a monitor (resolution of 1920x1080; refresh rate of 120Hz) and using MATLAB - Psychtoolbox software. Eye movements were tracked and recorded monocularly recording the movements of the right eye. The sentences were presented in a monospaced *Courier* font black colour on a light off-white background. Each trial began with participants focusing their gaze on a fixation check dot on the left of the sentence and would end when they would focus their gaze to the end-dot to the right of the sentence.

tACS Stimulation Condition

The three brain stimulation conditions were left hemispheric stimulation; right hemispheric stimulation; and sham stimulation condition which acted as a placebo condition. Both left and right conditions were stimulation conditions with frequency of the alpha band (10 Hz) and the current of 1.5 mA which was set based on previous literature (Wischnewski et al., 2022). The sham condition which was our placebo control consisted of stimulation ramping up to 1.5 mA over 30 seconds and then 30 seconds of stimulation so that the participants could feel some stimulation and after that the stimulation would turn off. The spots that were stimulated were indicated and fixated with the usage of an EEG cap and electrodes were placed on O1 and CP3 areas for the left hemisphere and O2 and CP4 for the right hemisphere. The regions that were stimulated were thus occipital and central parietal in each hemisphere. Stimulation was applied using an Eldith DC-Stimulator Plus (NeuroConn, Ilmenau, Germany).

Design

The id-sentence of the reading material was counterbalanced with stimuli condition, meaning that the same set of 60 sentences would appear in each block and therefore stimulation condition. The sentences were shuffled within each block for different participants and the questions would also follow the sentences randomly in a third of the trials; this was done to control for order effects within the reading condition.

The other experimental factor that was manipulated in this study was brain stimulation using tACS. The three reading blocks were paired with three different stimulation conditions (left, right, and sham) which were balanced using a simple Latin square that had 6 rows. The balancing was done in such a way that each condition was preceded and followed by the same condition an equal number of times, and each condition was in each ordinal position equally often. This way we counterbalanced across the experimental conditions to control for order effects and other confounds such as carryover effect.

Procedure

After reading the information about the study and signing the consent form, it was first checked that the participants' eyes were trackable by the eye tracker. Once this was established the participants' scalp was prepared for stimulation by cleaning of the areas and applying a conductive gel. The tACS electrodes were put on the predefined areas of the cranium. When the tACS was prepared the participants were instructed to put their head into the headrest at the side of the table, 72 cm away from the monitor. The participant was presented with the instructions for the reading task and a calibration was performed to tune the eye tracker. After the calibration the participant started with the practice block; if there were no questions or adjustments to be made, stimulation was started and the participant would start with the first experimental block. Between each block the stimulation condition was changed and participants were given the opportunity to take their head out of the headrest and we recalibrated the eye tracker before continuing with the experiment. After the final block the participants were asked to answer post-session questionnaires with which they concluded their participation.

Measures

For the present study, a relevant experimental measure was the duration the participant needed to read each sentence in different experimental conditions. This is defined as the time between the participant looking at the initiation spot on the left of the sentence and looking at the spot on the right of the presented sentence. Another measure of interest is the frequency of regressive saccades during the reading; a regressive saccade in our experiment is a backwards eye movement initiated during first-pass reading which goes at least to the previous word. The measure is operationalised as the total number of regressive saccades per trial.

Results

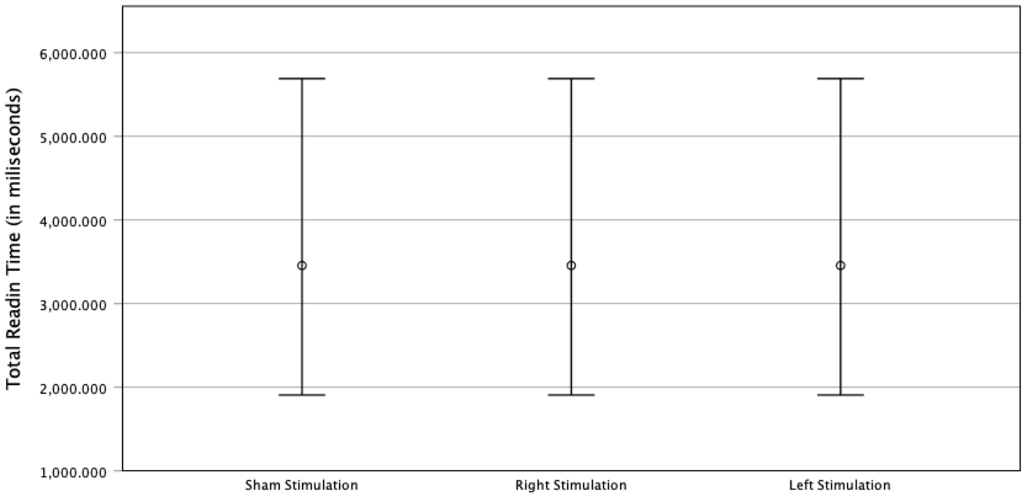
Accuracy as expressed in percentages of correctly answered questions per stimulation condition in natural reading is 89,1% for the sham condition, 92,8% for the left stimulation condition and 85,7% for the right stimulation condition. For the rest of the analysis the trials with incorrect responses were removed from the data thus controlling for comprehension in the reading task.

The measure with most relevance for my hypothesis is the total reading time of the sentences in the natural reading condition. After preprocessing of the data, the analysis was performed with the mean values of the reading time averaged across the experimental condition. Normal P-P plots were sketched for the mean reading values of each condition and they all revealed approximately normal distribution of the data, satisfying the assumption of normality.

Investigation of the means of the three conditions in milliseconds, left stimulation ($M = 3455.05$, $SD = 918.9$), right stimulation ($M = 3478.13$, $SD = 845.38$), and the sham condition (M = 3478.33, SD = 798.34) showed very small numerical differences (see *Figure 1*). A repeated measures analysis of variance was performed to test the within subject effects of the stimulation on total reading time. Mauchly's test indicated a violation of sphericity, $\chi^2(2) = 7.86$, $p = .020$; therefore, degrees of freedom were corrected using the Greenhouse–Geisser estimate of sphericity ($\varepsilon = .72$). After correction, the main effect of stimulation on average reading time was not statistically significant; $F(1.44, 24.45) = 0.25$, $p = .94$, partial $\eta^2 = .001$. The reported results of the repeated measures ANOVA did not support my first hypothesis, predicting an effect of left stimulation condition on total reading time.

Figure 1:

Plot of Total Reading Times in Separate Stimulation Conditions in Natural Reading



Despite the analysis of reading time showed no significant main effect, an additional analysis was performed to test for potential effects of stimulation on the proposed mediator variable - number of regressions. The means of the number of regression between conditions; left stimulation (M = 1.68, SD = 1.1), right stimulation (M = 1.67, SD = 1.12), and the sham condition (M = 1.72, SD = 1.0), again show small numerical differences. Similarly, a repeated measures ANOVA was performed to test the within subject effects of stimulation on the average number of regressions per trial. Inspecting assumptions, Mauchly's test indicated a violation of sphericity, $\chi^2(2) = 7.67$, $p = .022$. In response to the violation a correction was applied; degrees of freedom were corrected using the Greenhouse–Geisser estimate of sphericity (ε = .72). The effect of stimulation on average number of regressions per trial was not statistically significant; $F(1.45, 24.62) = 0.01$, $p = .84$, partial $\eta^2 = .006$. These results do not support the proposed effect of stimulation condition on number of regressions. Since the main effect of stimulation on average reading time, and the effect of stimulation on the number of regressions were both not significant, the conditions for a mediation model were not met. The mediation analysis was therefore not performed and the results do not support the second hypothesis predicting an effect of stimulation on total reading time, mediated through an average increase of regressions per trial.

As part of exploratory analysis, I was interested in potential differences in reading times between blocks of stimulation in trials with the moving window paradigm. As before, a repeated measures anova was run to test whether the tACS has an effect on reading time when controlling for the parafoveal preview. The effect of stimulation on total reading time in the reading window was not statistically significant; $F(2, 34) = 0.53$, $p = .59$, partial $\eta^2 = .06$. Observing numerical values, the difference between the mean value of total reading for left stimulation ($M = 4397.5$; $SD = 1161.2$), right stimulation condition ($M = 4439.9$; $SD = 1081.4$), and sham condition ($M = 4600.8$; $SD = 1215.3$) is somewhat larger than the difference in natural condition. However as the repeated anova showed no significant differences, no further analysis, such as paired t-tests was performed.

As the last result to be reported, 9 participants correctly guessed in which block the sham stimulation condition was applied. This represents 50% of the sample and is above the guessing rate as a result as there were 3 options to choose from corresponding to three conditions.

Discussion

The purpose of the present study was to investigate the role of visual attention in a reading task; explicitly, trying to manipulate the visual attention using transcranial weak-current stimulation over the occipito-parietal areas. The experimental hypotheses were based on theorising and previous results on the role of alpha oscillations in visuospatial tasks (Kasten et al., 2020; Kemmerer et al. 2022), and the role of alpha in reading as measured with EEG (e.g. Kornrumpf et al., 2017). Hypothesis 1 predicted an overall increase of reading time for the left stimulation condition compared to the right stimulation condition and the sham condition. The second hypothesis builds upon the first, proposing an explanation for the increased reading time through the increase of the number of regressions as a mediator. As seen in results, none of my hypotheses were significant which means no direct theoretical conclusions can be drawn from my analysis. However, there are still aspects of my findings that warrant further discussion.

Limitations and Further Directions

The results of the analysis can be interpreted through both a methodological and a theoretical perspective. Concerning methodology, the limitations of the current approach and suggestions for the future experimental investigations can be considered. In terms of limitations, the first thing that can be identified is the relatively low sample size. A higher sample size of participants would improve the experimental power of our study. The a priori power analysis I ran was based on previous studies using tACS in visuospatial tasks. I had decided to conduct a power analysis for a paired sample t-test as I was interested in specific differences in reading time between individual experimental conditions. However, since the repeated measures anova showed no significant differences further paired t-tests were not performed. Nevertheless, the required sample size according to my a priori power analysis was 34, and so by this condition the current sample was underpowered.

The results of the current study show no evidence for an effect of stimulation; the reason for this could be both in the task design and in the experimental conditions. Firstly, it is possible that the reading task and the way it was designed did not allow for conditions where an effect of the stimulation could be recorded. One possible explanation in this sense would be that the sentence material was inappropriate for the stimulation to show an effect on speed of reading. The participants were asked to read one-line sentences, some of which were as short as 6 words; it is possible that reading speed did not show any changes across experimental conditions because sentences were too short. A possible explanation for this is that due to the length of the sentences, participants could not reach their asymptotic reading speed. Another possibility is that the effect on parafoveal preview is not significant as there is less benefit when there are only a few words to preview. In other words, even if there was an effect of stimulation on visual attention and consequently reading duration, it was so small that it did not affect the total outcome of these short one-line sentences. It is possible that the levels of visuospatial attention needed for such short sentences remained sufficient even in the case of left stimulation where it was predicted that the experimental condition will disrupt the attention process. Following this idea, a suggestion for future research would be to test this experimental design or longer pieces of text, such as paragraphs. Perhaps the effect of stimulation on visuospatial attention and the reading process is cumulative and was therefore not present in these single sentence trials.

Furthermore, it is possible that the task exposure was too limited to show any effects of electrical stimulation on attention and therefore reading time. Given that the number of trials in the present main analysis was only 90 sentences; 30 trials per block, it is possible that the increase in number of trials would show better signs of possible effects of stimulation on reading duration. Considering a combination of both the sentence length and the number of trials, it is possible that the experimental task and procedure did not provide conditions needed for an experimental effect.

Considering the experimental condition, a possible limitation of the stimulation would be the set value of electrical current used in stimulation was too weak to show a significant effect. In the study, 1.5 mA was the set strength of electrical current stimulation; this value was selected based on previous experimental literature. Wischnewski et al. (2022) report the typical range of current intensity in tACS between 0.2 and 4 mA. More specifically for example, Kemmerer et al. 2022 reported significant effects of neuromodulation of attention in a visuospatial task while stimulating with the electrical current of 1.5 mA using tACS. Furthermore, Kasten et al. (2020) who show significant effects of tACS neuromodulation in an attention task used an intensity of 2mA in their stimulation. Considering the typical range as reported in the Wischnewski et al. (2022) overview, 2mA is still relatively far from the high-end values of stimulation. It seems that the research field of reading and attention could benefit from studies looking into differences between stimulation current strength and how they affect possible effects.

Concerning the current study, some suggestions for future research would start with a proposition for a higher sample size. A redesign of the current experiment would likely benefit from longer sentence materials and an increase in the number of trials. In regards to the experimental condition, an increase of electrical current of the stimulation can be considered. It is possible that implementation of these considerations in a future study would improve the chances of a significant effect of the experimental condition.

Concerning the research niche of transcranial stimulation in reading and attention tasks some broader further directions and suggestions can be proposed. Given that humans differ in levels of reading skill and capability, sensitivity of the experiment could be increased if the general reading level would be accounted for. Similarly, humans differ in their attentional capacities (Robison et al., 2023); again, it is possible that the accuracy of the stimulation effects on the performance would be increased if the attentional predispositions of individuals would be accounted for. For example, it could be interesting to run this experiment on a sample of participants with reading difficulties, or to adapt it for people with specific neural diversities connected to attention such as ADHD. tACS could have specific effects on subsamples of the population that struggle with either reading or attention and these would not be seen in the present study. The research field of non-invasive brain stimulation is relatively young and its implementation in reading tasks is quite novel meaning every experimental finding is a step towards new theoretical understanding.

Theoretical Implications

Given the non-significant state of present results there are no real-world practical or therapeutic implications to be drawn from the present study. Considering theoretical implications, as stated before, no direct conclusions can be drawn. One possible suggestion for an implication based on our null results is that the tACS stimulation does not affect the reading speed and therefore duration. However, given the outlined limitations this is not certain.

One interesting finding which is consequently related to the theoretical proposition of the current study can be found when investigating the numerical values of the total reading time averages. The first hypothesis of the present study proposes a longer reading time for the left stimulation condition compared to the right and the sham stimulation condition. Even though the differences between the three conditions are not significant, comparing the total reading time of the right stimulation condition and the sham condition shows that the two are almost identical. This is in line with the theoretical base of the proposition that stimulation will only have an effect when stimulation is applied to the left hemisphere when our visual attention is directed to the right like it is in natural reading. This is in line with Worden et al.

(2000) who showed that amplitudes of alpha oscillations decrease contralateral to the attended area. In the case of reading in the Western world the attention is biased towards the right of our visual field and therefore amplitudes of alpha oscillations are decreased in the left hemisphere. Conversely, the amplitudes in the right hemisphere are higher (Kornrumpf et al., 2017). If tACS can increase amplitudes of alpha oscillations and therefore affect attentional processes then we would expect an effect in the left hemisphere where the amplitudes are lower, when attending right. On the other side, the present study hypothesised no experimental effect when stimulating the right side, predicting a ceiling effect of a sort in terms of inhibition role that higher amplitudes of alpha oscillations play in the right hemisphere. It seems that this consequential implication of our hypothesis is valid given that there is virtually no numerical difference between total reading time in the right stimulation condition and the sham condition.

A possible implication of the present study is therefore that the tACS stimulation will only show effects on performance when stimulating the left hemisphere. Interestingly, previous studies working with tACS in visuospatial tasks such as Posner's paradigm have shown stronger results stimulating the left hemisphere (e.g., Kemmerer et al. 2022; Kasten et al., 2020). This is also in line with previous EEG studies showing stronger alpha power dynamics in the left hemisphere (Okazaki et al., 2014). In the present study, it seems, the amplitudes of alpha oscillations in the right hemisphere may have reached a certain height resulting in a functional plateau. Therefore stimulation of the right hemisphere which would hypothetically additionally increase those amplitudes does not seem to affect the performance.

Conclusion

Taken together, the results of our experimental study showed no significant effects supporting the hypothesised predictions. The differences in total reading times in respective experimental conditions were non-significant for both the natural reading which was the main hypothesis and reading with a window paradigm which was a part of exploratory analysis. Despite this, the present study contributes to the field of non-invasive brain stimulation and studies of visual attention in reading. To the author's best knowledge, application of tACS in a reading task is a novel contribution to the research field. In this sense it may serve as a theoretical and practical pilot study for future experimental investigations.

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