

**Alpha-tACS and Attention During Reading: the Role of Individual Differences in
Sustained Attention**

Paula Drenth

S5119243

Department of Psychology, University of Groningen

PSB3E-BT15: Bachelor Thesis

2425_2a_37_EN: Attention and brain rhythms in reading

Supervisor: Dr. Olaf Dimigen

Second evaluator: Dr. Tassos Sarampalis

In collaboration with: Ana-Mateea Cerchez, Klar Opraus, Basak Saraçoglu, Noe Stickel,

Koen van Os

1 July 2025

A thesis is an aptitude test for students. The approval of the thesis is proof that the student has sufficient research and reporting skills to graduate, but does not guarantee the quality of the research and the results of the research as such, and the thesis is therefore not necessarily suitable to be used as an academic source to refer to. If you would like to know more about the research discussed in this thesis and any publications based on it, to which you could refer, please contact the supervisor mentioned

Abstract

Reading is a complex cognitive process that is dependent on both visual and attentional control. In this process, eye movements can offer direct insight into cognitive effort and comprehension. Alpha-oscillations (8-12 Hz) are recognised as a key mechanism in attentional control. This bachelor thesis investigates whether alpha transcranial alternating current stimulation (tACS) might be able to influence attention during reading - as measured by eye movement parameters such as gaze duration and regression frequency – and whether individual differences in sustained attention – measured via the Mind-Wandering Questionnaire (MWQ) – moderate this effect. In a within-subjects design, 18 participants completed a reading task under three stimulation conditions: left-, right- and sham stimulation. Eye tracking was used to measure gaze duration, regression frequency, and total reading time. Additionally, the MWQ was utilized to assess mind-wandering tendencies. Even though alpha-tACS did not suggest any main effects on gaze duration, regression frequency and total reading time, a significant interaction effect was observed for stimulation condition x mind-wandering tendencies. Participants with high mind-wandering tendencies showed reduced reading times under stimulation, while participants with low mind-wandering tendencies read more slowly. This suggests that alpha-tACS may be dependent on individual differences like mind-wandering tendencies. These findings highlight the importance of individual differences in neurostimulation effects and suggest that alpha-tACS may be a potential meaningful intervention for clinical populations with attention- and reading deficits, such as ADHD and dyslexia.

Keywords: alpha-tACS, sustained attention, mind-wandering tendencies, eye-tracking, neurostimulation, alpha oscillations

Alpha-tACS and Attention During Reading: the Role of Individual Differences in Sustained Attention

The following hypothetical case of Sophie illustrates the behavioural profile of a neurodevelopmental comorbidity: Sophie is a 7-year-old girl who frequently loses focus during reading sessions. Instead of following along with the text, she looks around the room. When she reads, she struggles with word recognition, often needing to reread sentences multiple times before understanding them. Consequently, she has been diagnosed with both dyslexia and attention-deficit/hyperactivity disorder (ADHD). Research shows a significant prevalence of comorbidity between dyslexia and other neurodevelopmental disorders, particularly between dyslexia and the inattentive dimension of ADHD (Brimo et al., 2021). Sophie's case exemplifies how difficulties in both attention and reading processes can impact a child's ability to engage with text. Since approximately 21% of children diagnosed with dyslexia also show signs of ADHD (Brimo et al., 2021), it is crucial to understand how sustained attention influences reading performance. This understanding can contribute to the development of targeted interventions, such as adaptive reading strategies or neurostimulation techniques, to support individuals struggling with attentional and reading impairments.

Reading

Reading is a complex cognitive process that relies on both visual and attentional mechanisms. Eye movements serve as a direct indicator of how visual information is processed, particularly during reading. Three primary types of eye movements can be distinguished in reading: forward saccades, fixations and backward saccades/regressions (Weger & Inhoff, 2006). Saccades are rapid, eye movements that shift the eye position from one part of the text to another, lasting approximately 25-60 milliseconds. During saccades, no new visual information is processed due to saccadic suppression. Fixations occur when the eyes remain relatively stable, focusing on a specific part of the text, lasting about 200-250 milliseconds.

During fixations, visual information is actively processed. Readers do not fixate on every word; they often skip predictable or familiar words while focusing more on complex or unfamiliar ones (White, 2008). Regressions are backward-directed saccades. Small regressions typically occur as corrections for oculomotor error. Larger regressions, however, typically occur when readers encounter comprehension difficulties. Regression rates are influenced by individual differences, such as inhibitory control mechanisms like inhibition of return (IOR) (Posner et al., 1985). This mechanism refers to the suppression of previously processed stimuli, encouraging an orientation towards novelty and making it less likely for readers to return to recently processed words. A study by Weger and Inhoff (2006) indicated that individuals with a more developed IOR tend to make larger regressions because they skip nearby, recently fixated words and instead make longer backward saccades toward earlier text when comprehension difficulties arise. Moreover, according to Everett and Underwood (1994), individual differences in eye movement control and vocabulary influence reading ability and regression behaviour as well.

Attention and Eye Movements

Sustained attention can be defined as “the ability to self-sustain mindful, conscious processing of stimuli whose repetitive, non-arousing qualities, would otherwise lead to habituation” (Robertson et al., 1997). It refers to the ability to maintain focus on tasks over time and is determined by a dynamic interplay between motivational-, arousal- and cognitive factors (Slattery et al., 2022). When sustained attention lapses, this can result in mind-wandering, where attention drifts away from ongoing tasks to unrelated thoughts. This shift can reduce the ability to maintain sustained attention on the primary task. It’s dependent on factors including executive control, resource allocation, motivation and task -demand and -difficulty (Welhaf & Banks, 2024).

Eye movements, such as fixations and regressions, are closely related to attention. Research suggests that they reflect how visual information is processed and how cognitive resources are distributed (Mathôt & Theeuwes, 2011). Fixations may indicate where attention is allocated, and their duration reflects the amount of processing required; greater cognitive effort or difficulty often results in longer fixation durations (Traxler et al., 2012). Regressions can indicate comprehension difficulties; when readers encounter challenging words, they may regress to earlier parts of the text to reanalyse and resolve confusion. Regressions therefore can be interpreted as relocation of attention to earlier parts of the text, usually done when the initial processing of the text was incomplete or incorrect (Traxler et al., 2012). Consequently, they might reflect cognitive effort aimed at understanding the material. Beside fixations and regressions, saccades play a role in attention allocation (Mathôt & Theeuwes, 2011). The length of a forward saccade is dependent on multiple factors, such as word frequency, predictability, and attentional state. Short saccades can be associated with detailed processing of (complex) text, whereas longer saccades may suggest more fluent, but potentially more shallow reading (Traxler et al., 2012).

Since it is thought that attention directly influences eye movements, knowledge about the neural mechanisms underlying this process helps understand attention allocation in both health and disease. Given the frequent comorbidity of reading- and attentional deficits, such knowledge could contribute to more targeted research and interventions that address the overlapping cognitive deficits. One of the neural mechanisms underlying the interplay between attention and eye movements are alpha oscillations.

The Role of Alpha Oscillations in Attention and Reading

Alpha oscillations play a crucial role in attentional control and visual processing. Alpha oscillations are brain waves with a frequency of 8-12 Hz, typically associated with relaxation and attention. Alpha power reflects the degree of synchronization in neural populations. An

increase in alpha power corresponds to stronger synchronization of neuronal activity, whereas a decrease in alpha power reflects desynchronization (Ikkai et al., 2016). Alpha oscillations are believed to be crucial for filtering information: increased, or more strongly synchronized, alpha power suppresses irrelevant- and enhances relevant information (Toscani et al., 2010). This hypothesis is called *functional inhibition* (Jensen & Mazaheri, 2010). A power increase of these oscillations occurs proactively, before the onset of anticipated distractors, helping the brain to suppress distracting information. The increase in anticipatory alpha power acts as an inhibitory mechanism, reducing neuronal excitability in sensory regions processing distractors, and therefore acting as a protective mechanism for cognitive tasks such as working memory and attention (Bonnefond & Jensen, 2024). Accordingly, alpha oscillations can be interpreted as a top-down mechanism involved in inhibitory control. The role of alpha oscillations on visuospatial attention works similarly. Enhanced alpha activity in regions ipsilateral to the attended location (Wang et al., 2016) and decreased alpha activity in regions contralateral to the attended location (Ikkai et al., 2016) suggests that alpha activity plays a role in suppressing irrelevant visual information, while enhancing focus on relevant information.

Recent research suggests that saccades are locked to the phase of alpha oscillations: during the peak of an alpha cycle, neuronal inhibition is strongest, suppressing visual attention. Conversely, during the trough (weakest inhibition), neuronal excitability peaks, creating a window for the uptake of visual stimuli (Pan et al., 2023). Clayton and colleagues (2017) support this and found that visual stimuli are better processed when presented at the trough of an alpha oscillation compared to its peak. Additionally, Pan and colleagues (2023) found that when the upcoming word has low lexical frequency (i.e. less common in the language), the timing needs to be optimized to ensure that visual attention is maximized when the eyes move to the challenging word. This explains why the locking of eye movements to the alpha phase is stronger in low-frequency words than in high-frequency words.

Transcranial Alternating Current Stimulation

Since research suggests that alpha oscillations may influence eye movements, a promising approach to investigating and potentially modulating this relationship is through transcranial alternating current stimulation (tACS). tACS is a non-invasive brain stimulation technique that modulates brain activity by applying weak, oscillating currents through electrodes placed on the scalp (Wischnewski et al., 2023). These currents are not strong enough to create an action potential, but instead, tACS are thought to cause neuronal membrane potentials to follow the rhythm of the stimulation and can influence spike timing. Ideally, the stimulation might result in phase locking and synchronization of neural networks. The stimulation can be modified and tuned to the frequency of intrinsic brain oscillations, such as alpha oscillations (Schutter, 2014; Wischnewski et al., 2023). Studies show that alpha-tACS over the visual cortex increases alpha power, even after the stimulation has ended (Kasten et al., 2016). As such, tACS is not only a promising approach in researching the relationship between alpha oscillations, attention, and eye movements, but also a promising candidate for intervention. The non-invasive stimulation may contribute to the development of interventions aimed at modulating the core underlying mechanisms of reading- and attentional deficits, like Sophie's developmental comorbidity.

Conclusion

To summarize the findings above: reading is a complex cognitive process involving eye movements (saccades, fixations, and regressions) and basic attentional mechanisms (Weger & Inhoff, 2016). These attentional mechanisms may directly influence eye movements during reading, in which they appear to reflect cognitive effort and comprehension difficulties (Mathôt & Theewes, 2011; Traxler et al., 2012). A neural mechanism called alpha oscillations (8-12 Hz brain waves) is thought to play a crucial role in both attentional control and visual processing, in which it may help to suppress irrelevant and distracting information (Ikkai et al., 2016; Jensen

& Mazaheri, 2010; Toscani et al., 2010; Wang et al., 2016). Research suggests that saccades may be locked to the phase of alpha oscillations; the peak of an oscillation is thought to suppresses visual attention while the trough offers a window for the uptake of visual stimuli (Clayton et al., 2017; Pan et al., 2023). Lastly, tACS can be used to modulate alpha oscillations, possibly resulting in phase locking and synchronization of neuronal populations (Schutter, 2014; Wischniewski et al., 2023). While previous studies have linked alpha oscillations to visual attention, little research has been performed on how directly modulating these oscillations through tACS might affect reading behaviour. The current study aims to examine the effects of alpha-tACS on attention, as reflected in eye movements during reading. Additionally, the study will investigate whether individual differences in sustained attention moderate this effect.

Research Questions and Hypotheses

Understanding this relationship could improve interventions for individuals with reading difficulties like dyslexia, especially with neurodevelopmental comorbidities like ADHD. Therefore, this study aims to answer the following research questions:

1. How does alpha-tACS affect attention during reading, as reflected in gaze duration and regression frequency?
2. What is the effect of alpha-tACS on reading performance in individuals with high- versus low sustained attention?

Based on previous findings, the first expectation is that alpha-tACS will lead to a reduction in regressions and shorter fixation durations during reading. Second, individuals with low sustained attention are expected to show greater improvements in reading performance (reduced fixation durations, fewer regressions, enhanced comprehension accuracy) compared to those with high sustained attention. Conversely, those with already high sustained attention may experience little to no benefit.

Methods

Participants

The study initially included 20 participants. Two participants were excluded due to poor-quality eye-tracking data (e.g. excessive blinking), resulting in a final sample of 18 participants. Their ages ranged from 19 to 29 years old, ($M = 21.5$, $s = 2.04$). Of the 18 participants, 27,8% identified as male ($n = 5$), and 72,2% as female ($n = 13$). Participants were asked to fill out a the *Edinburgh Handedness Inventory* (Oldfield, 1971) and provide information about their English language background. 88.8% ($n = 16$) of participants reported they were right-handed, 5,6% ($n = 1$) reported being left-handed, and 5.6% ($n = 1$) reported being ambidextrous. Of all 18 participants, one participant reported English as their native language. All participants reported no history of neurological or psychiatric disorders, including ADHD and dyslexia, which were set as exclusion criteria for participation in the study. Additionally, all participants had normal or corrected-to-normal vision.

The study *Neuromodulation of attention in reading* (study code: PSY-2425-S-0301) was approved by the Ethics Committee of the Faculty of Behavioural and Social Sciences (EC-BSS). Ethics approval was obtained before the recruitment of participants. Participants were selected through a combination of convenience sampling and opportunity sampling between April 22 and May 9. Twelve participants were personally recruited by the researchers (e.g. fellow students and acquaintances within the appropriate age range), eight participated through the SONA pool of the University of Groningen, which consists primarily of first-year psychology students. Participants from the SONA pool were rewarded with 2.5 SONA credits after participation. The personally recruited participants were not compensated.

Materials

Sentence materials were adapted from the University College of London (UCL) corpus of reading times (Frank et al., 2013), which consists of 205 English sentences drawn from

narrative texts. Sentences were manually chosen by the experimenters to ensure they did not exceed the maximum length of 100 characters, resulting in 180 sentences selected for the experiment (e.g. “*Harry smiled at his little brother*”). For sentences that did not already include a comprehension question in the original corpus, additional comprehension questions were constructed and added to assess participant’s reading comprehension (e.g. “*Did Harry have a younger sibling?*”).

The *Mind-Wandering Questionnaire* (MWQ; Mrazek et al., 2013) was used to assess participants’ mind-wandering tendencies, including items such as “*While reading, I find I haven’t been thinking about the text and must therefore read it again*”. The MWQ consists of five self-report items that capture the frequency of mind-wandering in daily life. Each item is rated on a 6-point Likert scale ranging from *Almost Never* to *Almost Always*. The MWQ has showed high internal consistency ($\alpha = 0.89$) and high test-retest reliability over a four-week interval ($r = .81$), supporting its reliability. Additionally, the MWQ has shown significant predictive validity.

MATLAB R2024b (Mathworks) was used in combination with Psychtoolbox to run the experiment and present the stimuli. Additionally, it was used to preprocess and analyse eye-tracking data.

Apparatus & Software

Eye movements were recorded monocularly using the EyeLink 1000 Plus eye tracker (SR Research). Participants were seated approximately 70 cm from a computer screen (resolution: 1920 x 1200 pixels; refresh rate: 120Hz), using a chinrest to minimize head movements. The eye-tracker was calibrated using a standard 9-point calibration. Fixations, saccades and regressions were detected using EyeLink’s default algorithms.

Transcranial alternating current stimulation (tACS) was administered using the Eldith DC-Stimulator Plus (NeuroConn). Stimulation was delivered through two rubber electrodes,

placed according to the 10-20 EEG system. In the left hemispheric condition, the active electrodes were placed on O1 and PC3. In the right hemispheric condition, the active electrodes were placed on O2 and PC4. Stimulation was applied at a frequency of 10 Hz (alpha frequency) with an intensity of 1.5 mA for the duration of one block of the reading task.

Design

The study employed an experimental, within-subjects design to examine the causal relationship between alpha-tACS and reading behaviour. The independent variable was the stimulation condition, using three levels of stimulation: left-hemispheric stimulation, right-hemispheric stimulation, and sham stimulation. The dependent variables were eye movement parameters, including gaze duration (GD) and regression frequency (RF), and reading performance parameters, including total reading time (TRT). Individual mind-wandering tendencies, measured by the MWQ, were used as a moderator variable. All participants were exposed to each condition. To reduce sequence effects, the sequence of the stimulation conditions was counterbalanced using a Latin square design. Participants were assigned to one of the counterbalancing orders.

Procedure

After arriving, participants were welcomed and asked to read an information letter and sign an informed consent form. Additionally, they completed a short pre-session questionnaire assessing demographic information and handedness.

Next, participants were seated at the eye-tracking setup where the table height was adjusted to ensure comfort and stability. To check whether the participant was trackable, the camera's focus was manually optimized, along with the pupil- and corneal threshold. Participants were asked to look at the corners of the computer screen to check for abnormalities.

Following the trackability check, participants were prepared for tACS. A plain EEG-cap was placed on the participant's head and four electrode sites (PC3, PC4, O1, O2) were

located using the 10-20 EEG system (Jasper, 1958). These sites were cleaned with *Nuprep* gel and wiped with a wet tissue to minimize impedance. Electrodes were prepared with conductive gel and then placed under the cap on the four sites. Placement was double checked and adjusted if necessary. Participants were reassured on the safety of the procedure and informed about sensations they might feel during stimulation (e.g. itching or burning).

tACS was applied at 10 Hz (alpha frequency) with a fade-in and fade-out protocol in each stimulation condition. The experiment consisted of two phases. During the habituation phase, stimulation amplitude gradually increased to a maximum of 0.75 mV. In the main phase of the experiment, which coincided a reading task, the amplitude was increased to 1.5 mV.

In the sham condition, the electrodes were placed identically to the placement of the active stimulation conditions (i.e. either targeting left- or right hemisphere, depending on the counterbalancing). A fade-in was applied, after which stimulation was delivered at 1.5 MV for a brief period of 30 seconds, followed by a fade out. No further stimulation occurred during the rest of the task. The brief stimulation was intended to mimic the initial sensation of active stimulation, without modulating alpha oscillations. The order of the conditions (left hemisphere, right hemisphere, sham) was counterbalanced across participants using a Latin square design.

During the stimulation, participants performed a natural reading task. Sentences were presented one at the time in the centre of the screen on a white background, in black monospaced *Courier New* font to ensure equal character width. Each sentence was displayed on a single line. A moving-window paradigm (McConkie & Rayner, 1975) was randomly applied to 50% of the sentences. In these trials, only four characters to the right of the participant's current fixation point were visible, while all other letters of the sentence were replaced with lowercase x's. The window moved along with the participant's fixation point. In non-moving trials, the entire sentence was fully visible. Each trial began with a fixation point

on the left of the sentence. Once participant focused on the point, the sentence or moving window appeared. The participants read the sentence at their own, natural pace. Once they were finished reading the sentence, they fixated on a fixation point on the far right of the screen to indicate they finished reading. Once fixation was detected, a new trial began.

On approximately 33% of the trials, a yes/no comprehension question was presented after the sentence had been read to assess understanding. Participants responded using the left and right arrow keys on the keyboard, after which they received feedback on whether their answer was correct or incorrect.

At the start of each block and as needed between trials, there was an opportunity for calibration and validation of the eye-tracker, as eye movements of participants were recorded during all the trials. After completing all the experimental blocks, participants filled out a post-session questionnaires. One of which focused on subjective experience of the stimulation, including questions on physical sensations (“*Did you experience any sensation that resembles flickering lights?*”), and whether they were able to tell apart the stimulation conditions (“*In which reading block do you believe you had the placebo condition?*”). Other questionnaires focused on mind-wandering tendencies (using the MWQ) and visual imagery. After completing the questionnaires, the participants received a debriefing.

Data Analysis

After completing the experimental task and questionnaires, the data were analysed using the following statistical methods.

To answer the research question “How does alpha-tACS affect attention during reading, as reflected in gaze duration and regression frequency?”, a repeated-measures ANOVA was conducted with stimulation condition (left, right, sham) as a within-subjects factor. The dependent variables were mean gaze duration (GD) and regression frequency (RF), which served as indicators of attention. Gaze duration reflects the amount of time attention is allocated

on a word, and is thought to be sensitive to changes in attention (Mathôt & Theeuwes, 2011). Regression frequency reflects the tendency to re-read previously viewed material, which is thought to be sensitive to attentional fluctuations or comprehension difficulties (Traxler et al., 2012).

To answer the research question “What is the effect of alpha-tACS on reading performance in individuals with high- or low sustained attention?”, a 2 (MWQ group: high vs. low) x 3 (stimulation condition: left, right, sham) mixed ANOVA was performed, with total reading time (TRT) as a dependent variable and indicator of reading performance. TRT reflects the total amount of time a reader spends reading and processing a sentence, including fixations and regressions. Therefore, it might be able to capture both sustained attention and integration processes, making it a sensitive measure of overall reading performance (Mathôt & Theeuwes, 2011; Traxler et al., 2012).

Participants were divided into high and low mind-wandering groups based on a median split of their mean MWQ-scores. The main analysis focused on the interaction effect between MWQ-group and stimulation condition, to explore whether alpha-tACS effects on reading performance differed depending on individual mind-wandering tendencies.

All data was analysed using JASP version 0.18.0.0. Assumptions for ANOVA were checked as well.

Results

Table 1

Mean gaze duration (GD), regression frequency (RF) and total reading time (TRT) per stimulation condition and MW-group

MW Group	Stimulation	TRT	GD	RF
High MW	Left	3447.84	249.85	2.53
High MW	Right	3378.60	249.11	2.62
High MW	Sham	3746.98	250.59	2.85
Low MW	Left	3464.07	241.18	2.88
Low MW	Right	3557.75	247.20	2.73
Low MW	Sham	3142.52	236.95	2.56

Note: TRT and GD measured in milliseconds (ms), RF measured in numbers per trial

Different dependent variables were selected for each research question to best match the attentional effect that was examined. For RQ1, in which attention was investigated in reflective eye-movement parameters, GD and RF were selected, as these could possibly indicate minimal, moment-to-moment attentional fluctuations during reading. For RQ2, which focused more on a global measure of reading performance, TRT was selected. Also, this parameter is thought to be more sensitive to individual differences in sustained attention, as it is dependent on a variety of eye movements, such as gaze duration, regression frequency and saccade length. This choice allows the analyses to align more precisely with the focus of each question.

Research question 1: Main Effect of Stimulation

To answer the first research question: “How does alpha-tACS affect attention during reading, as reflected in fixation duration and regression frequency?”, repeated-measures

Analyses of Variance (ANOVA) was used. First, the effect of stimulation-condition (left, right, sham) on gaze duration was investigated.

The sphericity-assumption was assessed using Mauchly's test. Because this assumption was violated (Mauchly's $W = 0.461$, $p = .002$), a Greenhouse-Geisser correction was used to minimize the possibility of false positives. Normality of gaze duration data was assessed using Q-Q plots for each stimulation condition, which indicated no substantial deviations from normality. Therefore, the assumption of normality was considered to be met.

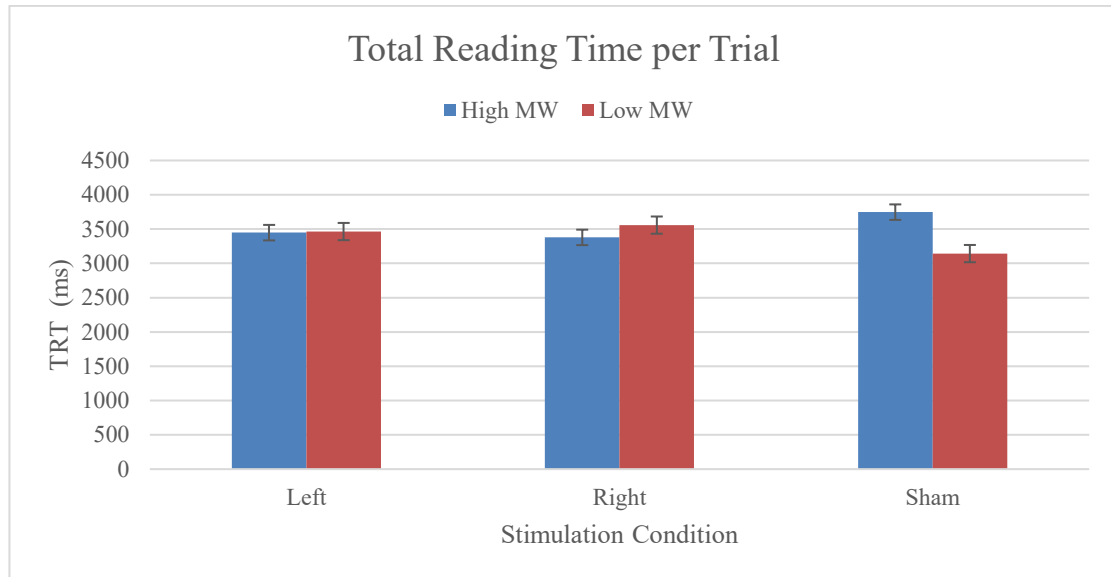
Descriptive statistics (**Table 1**) show very small numerical differences in gaze duration between conditions. Accordingly, results of the RM-ANOVA showed that the effect of alpha-tACS on gaze duration was non-significant, $F(1.300, 22.039) = 0.506$, $p = .532$, $\eta^2_p = .029$ (small effect). This means that no evidence for significant differences were observed in the effect of stimulation conditions (left, right, sham) on gaze duration. Not only did the means display minimal numerical differences, this was also supported by the results of the RM-ANOVA.

Second, the effect of stimulation-condition (left, right, sham) on regression frequency was investigated. Similar results were found for Mauchly's test and the Q-Q plots for regression frequency as for gaze duration. Descriptive statistics (**Table 1**) show very small numerical differences in regression frequency between conditions. Accordingly, results of the RM-ANOVA indicated that the effect of alpha-tACS on regression frequency was non-significant $F(1.448, 24.621) = 0.099$, $p = .844$, $\eta^2_p = .006$, indicating that no evidence for significant differences was observed in the effect of stimulation conditions (left, right, sham) on regression frequency. Again, the means displayed minimal numerical differences, which was then supported by the results of the RM-ANOVA.

Research Question 2: Effects of tACS and Mind-Wandering on Total Reading Time

Figure 1

Total Reading Time per Trial



To answer the second research question: “What is the effect of alpha-tACS on reading performance in individuals with high- or low sustained attention?”, a mixed-ANOVA was conducted. The analysis started with a 3 (stimulation condition: left, right, sham) x 2 (MW group: high, low) mixed-ANOVA to investigate the effects of stimulation condition and mind-wandering tendencies on total reading time (TRT).

Descriptively, **Table 1** reveals notable patterns in TRT across conditions. In the sham condition, low-MW participants read faster participants ($M = 3142.52$) than high-MW participants ($M = 3746.98$) with a difference of approximately 600 ms. Under left hemispheric stimulation, this gap narrowed: low-MW TRT increased slightly ($M = 3464.07$), whereas high-MW TRT decreased ($M = 3447.84$). Right-hemispheric stimulations showed a similar pattern, with low-MW TRT rising even further ($M = 3557.75$) and high-MW TRT decreasing ($M = 3378.60$).

The ANOVA confirmed a significant interaction between stimulation conditions and MWQ score for TRT, $F(2, 32) = 4.042$, $p = .027$, $\eta^2_p = .202$ (large effect). This suggests that

the effect of stimulation on TRT varied depending on whether the participant scored high or low on the MWQ.

Figure 1 indicates that in participants with low MW tendencies, TRT increases with stimulation – most with right stimulation. Critically, however:

1. There was no significant main effect of stimulation condition $F(2, 32) = 0.02, p = .978, \eta^2_p = .001$, indicating that the stimulation condition itself most likely did not affect TRT.
2. There was no significant main effect of mind-wandering tendencies, $F(1, 16) = 0.41, p = .532, \eta^2_p = .025$. This suggests no overall difference in TRT between high- and low mind-wandering tendencies.

Therefore, to further examine the interaction between stimulation condition and mind-wandering tendencies, an exploratory contrast was conducted comparing high vs. low mind-wandering tendencies, specifically within the sham condition, where the largest numerical difference of 600 ms was observed. The contrast was non-significant $t(19.382) = -1.437, p = .167$. Although in the post-hoc comparison, a moderate-to-large effect size was observed ($d = -0.681$), which together with the large numerical difference indicates a potentially meaningful difference.

Discussion

The aim of this research was to investigate to which extent alpha-tACS modulates attention during reading, as measured by eye movement parameters (gaze duration, regression frequency). Additionally, the influence of individual differences in mind-wandering tendencies – measured with the Mind-Wandering Questionnaire (MWQ) – on reading performance was investigated.

Attention plays a crucial role in reading, in which eye movements can give direct indications of cognitive effort and reading comprehension (Mathôt & Theeuwse, 2011; Traxler et al., 2012). Alpha-oscillations have been implicated as a key mechanism in visual attention (Ikkai et al., 2016; Jensen & Mazaheri, 2010; Toscani et al., 2010; Wang et al., 2016), raising the novel question of whether modulating these oscillations – e.g. through transcranial alternating current stimulation (tACS) – leads to significant differences in eye movement patterns during reading. The understanding of this relationship might offer a meaningful contribution to future research, which could focus on individually tailored clinical interventions for neurodevelopmental comorbidities such as ADHD and dyslexia.

To current study was conducted to answer the following research questions:

1. How does alpha-tACS affect attention during reading, as reflected in gaze duration and regression frequency?
2. What is the effect of alpha-tACS on reading performance in individuals with high- versus low sustained attention?

A within-subjects design was employed, in which participants took part in a reading task under three stimulation conditions (left, right, sham) while their eye movements were recorded. Additionally, they completed the Mind-Wandering Questionnaire (MWQ) to assess individual differences in attention. The following results were observed: no main effects were found for tACS on gaze duration (GD), regression frequency (RF), and total reading time

(TRT). However, a significant interaction effect between stimulation condition $\times$ mind-wandering (MW) tendencies was observed for TRT, together with a large numerical difference between low- and high MW tendencies in the sham condition. This ~ 600 ms slower reading time in high-MW participants during the sham condition might just show natural variability. However, its consistency with the MWQ's purpose of capturing individual differences in sustained attention, lends credibility to the idea that individual differences in mind-wandering tendencies might manifest in measurable reading-speed differences. Together with the statistically significant interaction effect between stimulation condition $\times$ MW tendencies observed for TRT and the numerical difference between high- and low MW tendencies disappearing with stimulation, this might suggest that mind-wandering tendencies play a critical role in individual responses to tACS.

As mentioned above, the results showed that individuals with high MW tendencies showed reduced reading time under stimulation, whereas individuals with low MW tendencies showed an increase in reading time. This indicates that tACS might enhance focus in individuals with lower baseline sustained attention, but may interfere with natural attentional processing in individuals with already stable attention.

These findings align partially with previous research on alpha oscillations and attention. Even though several studies have reported that alpha-tACS can increase alpha power and enhance performance on simple attentional tasks (Kasten et al., 2016), no main effects of tACS were observed in the current study. The absence of main tACS effects may stem from our use of a fixed 1.5 mA intensity. The fixed stimulation may not have been ideal for every participant, given individual differences in cortical excitability and responsiveness to neuromodulation (Krause & Kadosh, 2014). The effects of tACS have shown to be strongest when stimulation frequency closely matches the individuals baseline oscillation frequency (Zanto et al., 2021), and this was not accounted for in the current research.

Additionally, the selected eye movement parameters, namely gaze duration and regression frequency, might not be optimal operationalizations of sustained attention. Although commonly used in reading research and reflective of cognitive effort and comprehension (Mathôt & Theeuwes, 2011; Traxler et al., 2012), they are influenced by multiple other factors such as word frequency, complexity, and predictability (Rayner et al., 2016; White, 2008). Consequently, they may not provide an optimal presentation of sustained attention which could prevent the detection of the already subtle changes induced by tACS. However, the large numerical difference in TRT between high- and low-MW groups (~600 ms) suggests that TRT—a global measure—may better capture attentional differences.

The observed interaction effect between stimulation condition and MW tendencies aligns with previous research that describe alpha oscillations as a top-down mechanism of attention. Previous studies suggest that increases in alpha power are associated with the suppression of irrelevant information, while enhancing task-relevant information (Jensen & Mazaheri, 2010; Toscani et al., 2010). For example, Bonnefond and Jensen (2024) suggest that anticipatory increases in alpha power serve as a protective mechanism against distracting and irrelevant information during cognitive demanding tasks. This partially aligns with the observed interaction effect from the current study; individuals with high MW tendencies benefit from tACS, but the stimulation might cause disadvantage in individuals with low MW tendencies. An explanation for this could be that tACS works *state-dependent*, meaning that the effect of tACS is most likely depended on the current brain state. tACS is most effective when the targeted neural area is in an optimal receptive state – when there is sufficient room for improvement (Schutter, 2014). This would explain why individuals with high MW tendencies benefit more from tACS than individuals with low MW tendencies, namely, they have more room for improvement in context of their attention. Wischniewski and colleagues (2023) suggest that cognitive performance depends on a balance between neural oscillations

at different frequencies. Stimulating at alpha-frequency with tACS can enhance performance by restoring the balance when it was unstable, but it might disturb performance when it was stable. According to the review of Wischnewski and colleagues (2023), this balance might follow an inverted U-curve: too little or too much activity at a certain frequency (e.g. alpha) can harm performance, while a moderate level is optimal. This could explain why alpha-tACS helped individuals with high MW tendencies by bringing them closer to the optimal level. In contrast, individuals with low MW and probably a quite stable attention, might have been pushed past their optimal point, leading to worse performance.

A strength of the current study is the within-subjects design, where stimulation conditions were counterbalanced across participants. Every participant went through all tACS conditions (left, right, sham) in a counterbalanced order, minimizing order-effects and noise due to individual differences. Additionally, the inclusion of MW tendencies as a moderator shows the importance of the influence of individual variability on the efficacy of neurostimulation. However, there are also some limitations within the study that need to be addressed. The first is the small sample size ($n = 18$), which limits the statistical power of the research, enhancing the possibility of type II errors. Second is the operationalization of sustained attention, measured by eye movement parameters. Gaze duration and regression frequency might be, while reflective of cognitive effort and comprehension, limited in their ability to detect actual changes in sustained attention. These parameters are influenced by many other factors besides attention. Subtle changes caused by alpha-tACS might be undetectable due to the operationalization of sustained attention.

Future research should further investigate the conditions under which tACS is most effective. To ensure statistical power and generalizability, it should focus on larger sample sizes. Additionally, combining tACS with EEG measurements could help verify whether alpha oscillations were successfully modulated in targeted brain regions. The current study

highlights the importance of individual variability in responsiveness to tACS, which should be taken into account in future research as well. Finally, including participants with ADHD, dyslexia or comorbidities could provide valuable insights into the efficacy of tACS in clinical populations. Consequently, tACS could be used as a low-cost clinical application for neurodevelopmental comorbidities such as ADHD and dyslexia. However, since individual variability probably plays a role in the efficacy of tACS, individual oscillatory patterns should be examined before the implementation of tACS applications and tACS applications should be individually tailored.

Conclusion

To answer the main research question “To what extent does alpha-tACS modulate attention during reading, as measured by eye movement parameters, and how is this effect moderated by individual differences in sustained attention?”: the results indicate that alpha-tACS did not produce any direct effects on attention during reading as measured by eye movement parameters (gaze duration, regression frequency). However, an interaction between mind-wandering tendencies and stimulation condition suggests that total reading time might be moderated by individual differences in sustained attention. Specifically, alpha-tACS decreased total reading time in individuals with high mind-wandering tendencies, while increasing total reading time in individuals with low mind-wandering tendencies. This finding highlights the importance of individually tailored approaches to neurostimulation and offers opportunity for future research on efficacy of tACS in clinical populations such as ADHD and dyslexia.

References

- Bonnefond, M., & Jensen, O. (2024). The role of alpha oscillations in resisting distraction. *Trends in Cognitive Sciences*. <https://doi.org/10.1016/j.tics.2024.11.004>
- Brimo, K., Dinkler, L., Gillberg, C., Lichtenstein, P., Lundström, S., & Johnels, J. Å. (2021). The co-occurrence of neurodevelopmental problems in dyslexia. *Dyslexia*, 27(3), 277–293. <https://doi.org/10.1002/dys.1681>
- Clayton, M. S., Yeung, N., & Kadosh, R. C. (2017). The many characters of visual alpha oscillations. *European Journal Of Neuroscience*, 48(7), 2498–2508. <https://doi.org/10.1111/ejn.13747>
- Everatt, J., & Underwood, G. (1994). Individual differences in reading subprocesses: relationships between reading ability, lexical access, and eye movement control. *Language and speech*, 37 (Pt 3), 283–297. <https://doi.org/10.1177/002383099403700305>
- Henderson, J. M., & Ferreira, F. (1990). Effects of foveal processing difficulty on the perceptual span in reading: Implications for attention and eye movement control. *Journal of Experimental Psychology Learning Memory and Cognition*, 16(3), 417–429. <https://doi.org/10.1037/0278-7393.16.3.417>
- Ikkai, A., Dandekar, S., & Curtis, C. E. (2016). Lateralization in Alpha-Band Oscillations Predicts the Locus and Spatial Distribution of Attention. *PLoS ONE*, 11(5), e0154796. <https://doi.org/10.1371/journal.pone.0154796>
- Jasper, H. H. (1958). The ten-twenty electrode system of the international federation. *Electroencephalography And Clinical Neurophysiology*, 10, 371–375.
- Jensen, O., & Mazaheri, A. (2010). Shaping functional architecture by oscillatory alpha activity: gating by inhibition. *Frontiers in Human Neuroscience*, 4. <https://doi.org/10.3389/fnhum.2010.00186>

Kasten, F. H., Dowsett, J., & Herrmann, C. S. (2016). Sustained Aftereffect of α -tACS Lasts Up to 70 min after Stimulation. *Frontiers in Human Neuroscience*, 10. <https://doi.org/10.3389/fnhum.2016.00245>

Krause, B., & Kadosh, R. C. (2014). Not all brains are created equal: the relevance of individual differences in responsiveness to transcranial electrical stimulation. *Frontiers in Systems Neuroscience*, 8. <https://doi.org/10.3389/fnsys.2014.00025>

Luke, S. G. (2018). Influences on and consequences of parafoveal preview in reading. *Attention Perception & Psychophysics*, 80(7), 1675–1682. <https://doi.org/10.3758/s13414-018-1581-0>

Mathôt, S., & Theeuwes, J. (2011). Visual attention and stability. *Philosophical Transactions Of The Royal Society B Biological Sciences*, 366(1564), 516–527. <https://doi.org/10.1098/rstb.2010.0187>

MathWorks. (2024). *MATLAB (Version R2024b)* [Computer software]. <https://www.mathworks.com>

McConkie, G. W., & Rayner, K. (1975). The span of the effective stimulus during a fixation in reading. *Perception & Psychophysics*, 17(6), 578–586. <https://doi.org/10.3758/bf03203972>

Mrazek, M. D., Phillips, D. T., Franklin, M. S., Broadway, J. M., & Schooler, J. W. (2013). Young and restless: validation of the Mind-Wandering Questionnaire (MWQ) reveals disruptive impact of mind-wandering for youth. *Frontiers in Psychology*, 4. <https://doi.org/10.3389/fpsyg.2013.00560>

NeuroCare Group GmbH. (n.d.). *DC-Stimulator PLUS operator's manual*. NeuroConn. <https://www.neurocaregroup.com/>

Oldfield, R.C. (1971). *Edinburgh Handedness Inventory* [Database record]. APA PsycTests. <https://doi.org/10.1037/t23111-000>

Pan, Y., Popov, T., Frisson, S., & Jensen, O. (2023). Saccades are locked to the phase of alpha oscillations during natural reading. *PLoS Biology*, 21(1), e3001968. <https://doi.org/10.1371/journal.pbio.3001968>

Posner, M. I., Rafal, R. D., Choate, L. S., & Vaughan, J. (1985). Inhibition of return: Neural basis and function. *Cognitive Neuropsychology*, 2(3), 211–228. <https://doi.org/10.1080/02643298508252866>

Rayner, K., Schotter, E. R., Masson, M. E. J., Potter, M. C., & Treiman, R. (2016). So much to read, so little time. *Psychological Science in the Public Interest*, 17(1), 4–34. <https://doi.org/10.1177/1529100615623267>

Robertson, I. H., Manly, T., Andrade, J., Baddeley, B. T., & Yiend, J. (1997). 'Oops!': Performance correlates of everyday attentional failures in traumatic brain injured and normal subjects. *Neuropsychologia*, 35(6), 747–758. [https://doi.org/10.1016/s0028-3932\(97\)00015-8](https://doi.org/10.1016/s0028-3932(97)00015-8)

Schutter, D. J. (2014). Syncing your brain: electric currents to enhance cognition. *Trends in Cognitive Sciences*, 18(7), 331–333. <https://doi.org/10.1016/j.tics.2014.02.011>

Slaterry, E. J., O'Callaghan, E., Ryan, P., Fortune, D. G., & McAvinue, L. P. (2022). Popular interventions to enhance sustained attention in children and adolescents: A critical systematic review. *Neuroscience & Biobehavioral Reviews*, 137, 104633. <https://doi.org/10.1016/j.neubiorev.2022.104633>

SR Research. (n.d.). *EyeLink 1000 Plus user manual*. SR Research. <https://www.sr-research.com/>

Toscani, M., Marzi, T., Righi, S., Viggiano, M. P., & Baldassi, S. (2010). Alpha waves: a neural signature of visual suppression. *Experimental Brain Research*, 207(3–4), 213–219. <https://doi.org/10.1007/s00221-010-2444-7>

Traxler, M. J., Johns, C. L., Long, D. L., Zirnstein, M., Tooley, K. M., & Jonathan, E. (2012). Individual Differences in Eye-Movements During Reading: Working Memory and

Speed-of-Processing Effects. *Journal Of Eye Movement Research*, 5(1).
<https://doi.org/10.16910/jemr.5.1.5>

Veldre, A., & Andrews, S. (2014). *Lexical quality and eye movements: individual differences in the perceptual span of skilled adult readers*.
<https://www.semanticscholar.org/paper/Lexical-Quality-and-Eye-Movements%3A-Individual-in-of-Veldre-Andrews/19f1d382709c9d779fca5de2f372bd25b6733dff>

Wang, C., Rajagovindan, R., Han, S., & Ding, M. (2016). Top-Down control of visual alpha oscillations: sources of control signals and their mechanisms of action. *Frontiers in Human Neuroscience*, 10. <https://doi.org/10.3389/fnhum.2016.00015>

Weger, U. W., & Inhoff, A. W. (2006). Attention and eye movements in reading. *Psychological Science*, 17(3), 187–191. <https://doi.org/10.1111/j.1467-9280.2006.01683.x>

Welhaf, M. S., & Banks, J. B. (2024). Effects of emotional valence of mind wandering on sustained attention performance. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, 51(2), 238-254. <https://doi.org/10.1037/xlm0001369>

White, S. J. (2008). Eye movement control during reading: Effects of word frequency and orthographic familiarity. In *Journal of Experimental Psychology: Human Perception and Performance* (Vol. 34, Issue 1, pp. 205–223). <https://doi.org/10.1037/0096-1523.34.1.205>

Wischnewski, M., Alekseichuk, I., & Opitz, A. (2023). Neurocognitive, physiological, and biophysical effects of transcranial alternating current stimulation. *Trends in Cognitive Sciences*, 27(2), 189–205. <https://doi.org/10.1016/j.tics.2022.11.013>

Zanto, T. P., Jones, K. T., Ostrand, A. E., Hsu, W., Campusano, R., & Gazzaley, A. (2021). Individual differences in neuroanatomy and neurophysiology predict effects of transcranial alternating current stimulation. *Brain Stimulation*, 14(5), 1317–1329. <https://doi.org/10.1016/j.brs.2021.08.017>