The Moderating Role of Mind Wandering in Neuromodulation of Attention During Reading

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PSB3E-BT15: Bachelor Thesis
Group number 37

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July 1, 2025

Abstract

Alpha oscillations are linked to attentional control, a key cognitive process in reading. However, no prior research has investigated whether modulating alpha activity via non-invasive brain stimulation improves reading performance. In this study we investigated whether alpha-tACS influences attention in natural reading, and whether individual differences in mind wandering moderate its effects. 18 participants (median age= 21.5) completed a natural reading task under three stimulation conditions (left, right, sham alpha-tACS). Eye movements were recorded to measure total reading time, number of regressions and regression size. Mind wandering tendencies were measured using the 5-item Mind Wandering Questionnaire by Mrazek et al. (2013) and included in our analysis as a moderator. Our results showed no main effect of stimulation or mind wandering however a consistent interaction between mind wandering and stimulation was observed across all outcome variables. High mind wandering individuals showed improved natural reading, especially in the left tACS condition, while the low mind wandering individuals did not benefit from stimulation and in some cases performed worse. Our findings supported the state-dependent effects of alpha-tACS and emphasized the potential role of left hemisphere alpha in planning for upcoming words. Further investigation is required to confirm the moderating role of mind wandering and the association between alpha and forward planning in reading.

Keywords: alpha lateralization, attention, mind wandering, transcranial alternative stimulation, saccades

Alpha oscillations have been consistently linked to attentional control, particularly through the suppression of task-irrelevant information (Jensen at al.,2021; Peylo et al.,2021). Previous research has mainly focused on the role of alpha in spatial tasks therefore, the mechanisms through which alpha influences attention in reading remains unexplored (Ippolito et al., 2022). Transcranial alternating current stimulation (tACS) can provide insight into how alpha oscillations modulate attention in reading; however, its effect on reading performance has not been investigated yet. Moreover, the effectiveness of tACS may vary with individual differences in cognitive traits, such as mind wandering tendencies (Carrasco-Gomez et al., 2025). Given the central role of attention in reading and the potential for individual variability in tACS effectivity, it is important to investigate these interactions. Therefore, in this study, we aimed to answer the question "Does alpha-tACS modulate attention in reading measured through reading speed and number of regressive saccades?" and investigate if mind wandering tendencies moderate the effect of stimulation.

Reading and eye movements

Reading is a visual and cognitive process of making meaning out of a sequence of words; however, the mere recognition of individual words is not sufficient for successful reading. Readers must understand how the words connect to each other as well (Rayner et al., 2016). Consequently, it is not possible to read an entire paragraph at once or even a sentence at a single glance due to the constraint posed by visual acuity. Therefore, readers must make eye movements during reading to increase visual acuity. Specifically, the center of the vision called the fovea, has the highest acuity. In this region, visual information is analyzed with most detail and usually processed the fastest (Risse, 2012). Acuity gradually decreases in the parafovea, the area outside of our center of vision, about 1 to 5 degrees away from the fovea. The decrease in acuity limits us from seeing clearly and thus reading words outside the center our gaze.

During reading, saccades which are eye movements made on average every 250 ms, allow readers to efficiently move the fovea to the next word (Jensen et al., 2021; Rayner et al., 2016). During the fixation preceding a saccade, the eyes do not move as the reader fixates on the word in the fovea. The fixation duration varies depending on processing difficulty related to the properties of the reader and the currently fixated word (Rayner et al., 2016). Moreover, up-coming words can be pre-processed in the parafovea to some degree before the actual fixation occurs (Kornrumpf et al., 2017). This pre-processing guides the saccade toward the next words and thus enables fluent reading. Conversely, regressive saccades occur when the reader moves back to the previously processed word, often due to a failure in comprehension. Research shows that regressions also occur due to oculomotor aiming errors, as well as difficulties in word identification and in high-level semantic processing (Vitu & McConkie, 2000).

Previous literature has argued that attention, specifically pre-saccadic attention functions to prepare an eye movement by shifting visuospatial attention to the saccade target (Kornrumpf et al., 2017). Therefore, pre-saccadic attention shift allows for efficient reading by suppressing irrelevant, non-target information in “cluttered visual environments” (Zhao et. al, 2012). The concept of perceptual span plays an important role in explaining how attention is distributed during reading. Perceptual span is the region of effective vision from which useful information is acquired (Risse, 2012). Research indicates that perceptual span covers 12-15 characters to the right and 3-4 characters to the left of the fixation point, in English language (McConkie & Rayner, 1975). The moving window paradigm is used to study perceptual span. This gaze-contingent method includes a pre-defined window of visible text which moves with the reader’s gaze and outside the window text is hidden with Xs (Risse, 2012. Research suggests that all words within the perceptual span receive some degree of attention during fixation, as reducing the window size negatively impacts reading performance (McConkie & Rayner, 1975).

Role of alpha oscillations in reading and attention

Research has found that alpha amplitude, frequency ranging from 8-14 Hz, decreased contralateral and increased ipsilateral to the attended visual hemifield (Peylo et al.,2021). This asymmetry supports the idea that alpha rhythms are key mechanisms in navigating visual attention in reading. Alpha oscillations, dominantly present in the occipital and parietal cortex, are associated with inhibition of neuronal firing (Jensen at al.,2021). Occipital and parietal cortices, located in posterior regions of the brain, are responsible for visual processing of textual information (Price, 2012). Although alpha rhythms have been related to varying cognitive processes (e.g., memory, language, creative thinking), one of the clearest links is to the control of visuospatial attention (Ippolito et al., 2022). Alpha oscillations are thought to modulate attention through inhibition of task irrelevant information, at larger alpha amplitudes. This may be reflected in the attentional asymmetry observed in the occipito-parietal region during reading. During reading in left-to-right languages like English, the right visual hemifield is mostly ignored while the left visual hemifield is attended to (Peylo et al., 2021). This process is enabled by lateralization of alpha in the occipito-parietal region. Therefore, alpha lateralization is believed to facilitate reading by modulating attention to the upcoming word in the text and ignoring the already processed words on the left hemifield.

Previous research suggests that saccadic behavior during reading is aligned with the fluctuations in the alpha rhythms (Pan et al, 2023). Pan et al., (2023) found that saccade timing is adjusted based on the alpha phase, particularly when the next word is more challenging to process, such as those with lower lexical frequency. Building on Pan et al., (2023), it can be suggested that alpha rhythms may play a role in determining when and how often regressions are made to reprocess a difficult text.

The relevant question now is whether reading can be modulated through increasing or suppressing alpha rhythms using non-invasive brain stimulation. Investigating this question has considerable implications for the development of therapeutic interventions to enhance cognitive functions.

tACS and Alpha modulation

Transcranial alternating current stimulation (tACS) is a non-invasive brain stimulation method that can modulate attention in reading by generating oscillating electric fields (Herrmann, 2013). tACS applies weak alternating currents ranging from 1 to 4 mA through electrodes on the scalp which then pass through brain tissue. Instead of generating action potentials, tACS creates rhythmic fluctuations in the membrane potentials of neurons which then affect spike timing. Brain rhythms are temporally locked to an external alternating current, a process known as entrainment (Wischnewski,2023). In humans, entrainment of neurons can lead to modulation of cognitive processes even at lower doses of alternating currents (e.g 1-2 mA). For instance, Kasten et al. (2020) demonstrated that applying alpha-tACS over the left occipital cortex led an improvement in endogenous attention during a spatial cueing task. Similarly, Kemmerer et al. (2022) found that alpha-tACS over the parietal regions led to improved attention in a visuospatial task, further supporting the influence of alpha-tACS on attentional mechanisms. Given that alpha-tACS can modulate attentional processes through entrainment of neurons, it is likely that its effects may be moderated by individual differences in attentional control.

Attentional control as a potential moderator

As mentioned above, alpha waves have a role in regulating attentional control during reading, especially through influencing saccadic movements. Attentional control is the ability to regulate focus, selectively process information, and suppress distractions and hence it is essential for reading. Attentional inhibition is an important component of attentional control as it involves suppressing (task) irrelevant stimuli. The concept of attentional inhibition has been linked to reading efficiency, especially because it helps prevent orthographically similar words from entering working memory before they are ready to be processed (Arrington et al., 2023). Furthermore, previous research has found that alpha oscillations play a role in attentional inhibition in working memory. As mentioned in previous sections, increase in alpha amplitude is associated with suppressing task-irrelevant information and thus controlling attention (Sghirripa et al., 2021). Research has also demonstrated that students with weaker attentional inhibition mechanism and working memory performance have poor word recognition skills compared to their peers (Locascio et al., 2010). Therefore, inhibiting irrelevant stimuli appears to be critical for efficient reading.

Attentional control is thought to play a role in regressions through the mechanism of inhibition of return (IOR). IOR prevents us from attending again to recently attended locations and instead guides the eyes toward new text (Spalek & Hammad, 2005). Although the mainstream view on the purpose of regressions focuses on comprehension problems, research shows that regressions could also be driven by deficits in attentional inhibition mechanisms (Wegger & Inhoff, 2009). Studies have shown that saccade latencies increase when the eyes return to a previously fixated target, meaning it takes more time to initiate a regressive saccade than when moving forward to a new target (e.g word or object). This suggests that inhibitory mechanisms may guide saccades, as attention is biased to new input and hence, previously attended input is inhibited (Klein & MacInnes, 1999; Ro et al., 2000). Moreover, individual differences in IOR have been linked to differences in regression sizes and may be linked to differences in attentional inhibition mechanisms. Readers with faster IOR have been found to exhibit larger regressions as they attempt to avoid re-fixating recently read words, whereas those with slower IOR execute smaller regressions, suggesting that regression length and frequency may serve as indicators of attentional control difficulties (Wegger & Inhoff, 2009).

Attentional control is closely related to trait level mind wandering. Mind wandering can be defined by fluctuations in focus, specifically in shifting from task-related to task-unrelated thoughts (Smallwood & Schooler, 2006). Research has found that lower working memory capacity which may reflect poor attentional inhibition mechanisms, is associated with increased mind wandering (Kane et al., 2007). Specifically, mind wandering during reading has been linked to decreased text comprehension (McVay & Kane, 2012; Smallwood, 2011; Unsworth & McMillan, 2013), reinforcing the idea that lapses in attention contribute to difficulties in maintaining task-focused attention. Moreover, individuals with weaker attentional inhibition mechanisms are more likely to mind wander, as they struggle to sustain focus on the ongoing task (McVay & Kane, 2009).

The current study

In this report, we seek to answer the research question "Does alpha-tACS modulate attention in reading measured through reading speed and number of regressive saccades?".

Previous research has mainly focused on the role of alpha-tACS on modulating endogenous visuospatial attention in spatial cueing paradigms (Kasten et al.,2020; Kemmerer et al.,2022). However, the modulating effect of alpha-tACS in natural reading tasks has not yet been studied. Moreover, we explore the research question "Does mind wandering moderate the effect of alpha-tACS on the saccadic eye movements made during a simple reading task" focusing on the moderating role of individual differences in mind wandering.

Based on what was outlined in the previous sections, our hypotheses are as follows.

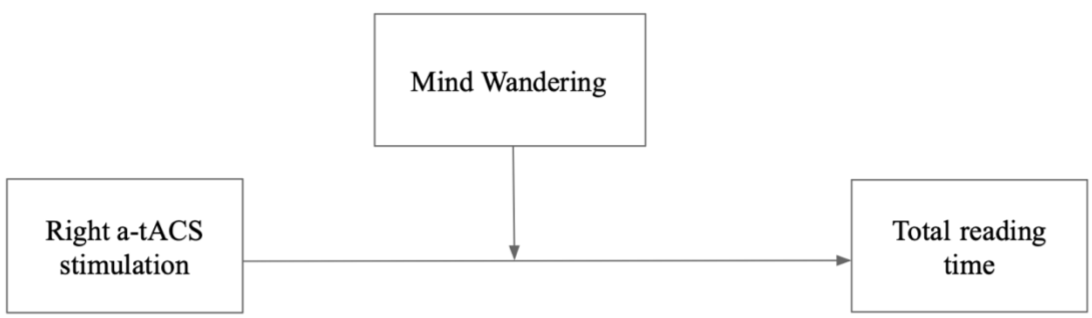
H1: Individuals with high mind wandering (vs. low mind wandering) have a shorter total reading time after right hemisphere alpha-tACS stimulation.

H2: Individuals with high mind wandering (vs. low mind wandering) make less regressive saccades after right hemisphere alpha-tACS.

H3: Individuals with high mind wandering (vs. low mind wandering) make larger regressions after right hemisphere alpha-tACS.

Figure 1

Moderating role of mind wandering tendencies during right alpha-tACS



As previous research has established that increasing alpha amplitude in right hemisphere suppresses irrelevant information on the left hemifield, individuals with high mind wandering will "benefit" more from right hemisphere tACS application since they have more difficulty in inhibiting irrelevant information when processing sentences.

Methods

Participants

We recruited 20 participants (ages 19-29, median= 21.5, 13 women). All participants were fluent in English, 19 of them were non-native speakers and the participants started acquiring English at the age of 8 on average. The participants were selected based on criteria to ensure that the stimulation works smoothly and attentional disorders are controlled for. These criteria included the absence of neurological or psychiatric disorders, no diagnosis of dyslexia, no skin diseases, no history of epileptic seizures, no tattoos or piercings on the scalp, and no metallic implants or bodily stimulators. If a participant did meet any of these criteria, they were thanked and dismissed from the study. According to the Edinburgh Handedness Inventory (Oldfield, 1971), 19 of the participants were right-handed. We used the SONA practicum to recruit first year psychology students, who were rewarded with 2.5 credits upon participating, as a part of course requirements. Additionally, we used volunteer sampling to recruit student peers and friends. These sampling methods were chosen due to practical and financial considerations. Our final dataset included 18 participants after filtering out one participant with poor fixation detection and the other to preserve the counterbalancing according to the Latin square method.

Word materials

As our research was on natural reading, we used a pre-existing corpus from Frank et al. (2013) with 361 sentences in English and yes/no comprehension questions for every third sentence (e.g., sentence: „To one side, out of sight of the priests on the steps of their temple, was a circle of stones “. Comprehension question: “Could the priests see the circle of stones?”). We selected 200 sentences for the actual experiment by editing out the shortest and the longest sentences from the corpus. Therefore, every stimulation block had 60 sentences, and the practice block had 20. Therefore, each participant completed 180 trials.

Overview over the design

The pilot study consisted of a 90-minute single session experiment divided into a short practice block and three standard blocks, with a different experimental condition in each block. The actual experiment with reading and neurostimulation took approximately 45 minutes and the rest of the time was used for preparation, questionnaires and short breaks between blocks. Within-subjects design was used with each participant participating in every stimulation condition. Moreover, a single-blind design was used, the participants were not informed on the stimulation condition. The order of the three stimulation conditions was counterbalanced using a Latin Square to prevent order effects due to potential residual effects of the previous condition as well as the reading speed changing over the course of the experiment, regardless of stimulation.

Brain Stimulation

In our experiment, the intended place of the tACS stimulation was manipulated. Eldith DC stimulator by NeuroCONN was used for tACS administration. In two of the experimental blocks, participants received neurostimulation on either the left or the right occipital and parietal lobes. There was a sham stimulation block where the tACS stimulation was stopped after 300 cycles (about 20-30 seconds) to mimic the initial tingling sensation of stimulation. Each stimulation block lasted approximately 15 minutes. Four electrodes were placed on the scalp using the 10-20 EEG system, on O2, O4 and PC3, PC4 nodes. The stimulation frequency was 10 Hz to match the alpha band.

Eye Tracking

Eye movements were recorded monocularly (only right eye) at a rate of 1000 Hz with a high-resolution eye tracker (EyeLink 1000 Plus, SR Research, United States) that was calibrated on a nine-point grid. The participants were seated at a viewing distance of 73.5 cm from a full HD monitor (1920x1080 pixels.) with a refresh rate of 120 Hz. Stimuli were presented using Psych Toolbox on MATLAB 24.2 (Brainard, 1997). One character on the screen 13 pixels wide = 0.32 degrees per character.

Moderator: Mind Wandering (MW).

To measure the extent of MW, the 5-item Mind Wandering Questionnaire by Mrazek et al. (2013) was used. Each item is coded on a 6-point Likert scale ranging from 1=Almost never to 6=Almost always. The scale included items such as “I have difficulty maintaining focus on simple or repetitive work.”. MWQ has good internal reliability (Cronbach’s alpha = 0.850) and good homogeneity with all items loading on a single component (Mrazek et al., 2013). Other moderators were also included in the experiment and are outside of the scope of this report.

Procedure

Upon arrival at the laboratory, participants were welcomed, and the experimenter reviewed the exclusion criteria with them once more to ensure eligibility. The participants completed a short presession questionnaire involving demographic information and completing the Edinburgh Handedness Inventory (Oldfield, 1971). The participants were then checked if their eyes were trackable and prepared for stimulation. Two electrodes were placed on both the right and the left occipito-parietal lobes at the same time. Only one hemisphere was stimulated in each block and the other two electrodes were left unconnected to the tACS device. First, there was a test run with 750 mA intensity (half of the current used for the experiment) which lasted for approximately three minutes, for the participant to get used to the sensations of the stimulation. The stimulation was delivered at an intensity of 1.5 mA with the condition order (left, right, sham) counterbalanced across participants using the Latin Square.

The reading task was self-paced and lasted approximately 10–15 minutes per block, including occasional recalibrations of the eye-tracker and responses to comprehension questions. Stimulation remained active throughout each block, up to a maximum of 15 minute. A break of approximately 5 minutes was provided between each stimulation block to allow the experimenter to change the stimulation condition.

Each trial began with a fixation dot on the left side of the screen. After fixating, a full sentence appeared, and participants read it from left to right. Fixation on a second dot on the right side of the screen triggered the next trial, creating a smooth and natural reading flow (see, e.g., Dimigen et al., 2011). In 50% of the trials, a gaze-contingent moving window paradigm was used, in which only four letters to the right of fixation were visible while the remaining text was masked with lower-case "X" characters but preserving inter-word spaces. This moving window followed the participant's gaze and allowed for measurement of the preview benefit, a marker of rightward attentional bias during reading. To ensure participant engagement, 33% of trials were followed by a yes/no comprehension question, which participants answered via clicking either left or right button of the mouse.

At the end of the experiment, any side effects experienced during each stimulation condition via a short questionnaire. They were also asked to guess the order in which they received each stimulation condition (left, right, sham). Finally, participants completed brief standardized questionnaires vividness of visual imagery, and general mind-wandering tendencies.

Statistical Analyses

The data was preprocessed on MATLAB 24.2 by the principal investigator. From the trials with comprehension questions, those with incorrect answers were removed. Saccades and fixations were detected with the default EyeLink online algorithm. Eye fixations shorter than 80 ms or longer than 1000 ms were excluded from the analysis. Moreover, trials with more than 2 blink events were excluded from analysis.

To test our hypotheses, we conducted analyses on Jeffrey's Amazing Statistics Program 19.3 (JASP). To test the main effect of stimulation, we used one-way repeated measures Analysis of Variance (RM-ANOVA) with three levels (right, left, sham stimulation).

Before testing our hypotheses, we conducted the Mauchly sphericity test to account for sphericity violation. If the sphericity assumption was violated, ANOVA results were again reported with the corrected degrees of freedom, using the Greenhouse-Geisser correction.

To test the interaction with MW, we used mixed ANOVA, with stimulation condition (right, left, sham) as a within-subjects factor and MW scores as a between-the-subjects factor. MW scores were coded as either 0 for low scores or 1 for high scores, split from the median. Furthermore, post-hoc pairwise comparisons were conducted, and we corrected for multiple comparisons using the Bonferroni correction.

Results

Main effect of stimulation

Table 1 gives an overview of the mean and standard deviation values for each measured variable before the moderator; mind wandering is considered. As can be seen from Table 1, there are no substantial numerical differences between means across stimulation conditions. For readability purposes, Table 1 only provides a simplified overview of stimulation effects collapsed across MW groups. Full descriptive statistics for all six experimental conditions (stimulation condition x MW) can be found in the Appendix .

Table 1

Descriptive statistics

Stimulation condition	Total reading time (ms)	Regressive saccades (n)	Regression size (visual angle)
Right tACS	3478.10 (869.90)	1.70 (1.00)	3.00 (1.00)
Left tACS	3455.10 (945.50)	1.70 (1.10)	3.20 (1.10)
Sham	3478.30 (821.50)	1.70 (1.20)	3.10 (1.20)

Note. Values are means, with standard deviations in parentheses.

To test whether the pattern observed in Table 1 was also true statistically, one-way RM-ANOVA was conducted. The one-way RM ANOVA revealed no significant main effect of stimulation on total reading time, $F (1.44, 24.50) = .03$, $p = .94$; on number of regressive saccades, $F (1.45, 24.62) = .09$, $p = .84$; or on regression size, $F (2, 34) = .23$, $p =.80$. This suggests no indication of stimulation effects prior to considering mind wandering as a moderator as none of the relationships were significant.

Hypothesis testing

Hypothesis 1

The first hypothesis predicted that individuals with high mind wandering (MW) tendencies would have a shorter total reading time following right hemisphere alpha-tACS stimulation compared to individuals with low MW tendencies.

Although not included in our priori-hypothesis, we tested the main effect of MW on total reading time with RM-ANOVA. We did not find a significant main effect, $F(1,16) =.41$, $p=.53$.

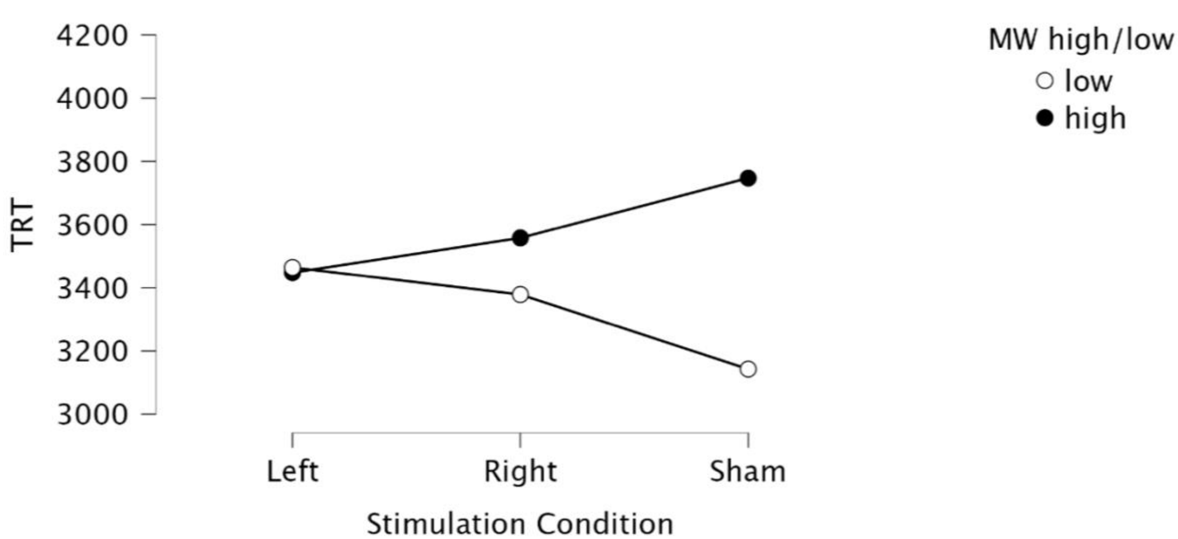
This suggests that high and low MW participants did not differ significantly in their total reading time. However, as reported in the next section, an interaction between MW and stimulation condition may provide further insight.

Figure 2 below displays the interaction effect between stimulation condition and MW level on total reading time (TRT). As shown in the figure, in the sham condition, high MW individuals had considerably longer reading times than low MW individuals, suggesting a clear disadvantage in the absence of stimulation.

Consequently, Mixed Analysis of Variance (ANOVA) found a statistically significant interaction effect of MW and stimulation condition on TRT with a large effect size, $F(2, 32) = 4.04$, $p = .03$, $\eta_p^2 = .20$.

Figure 2

Interaction of stimulation condition and MW level on total reading time (TRT)



However, post hoc comparisons revealed that the interaction effect was not in the direction we had hypothesized. Under right tACS, high MW participants read more slowly (M=3557.75, SD=931.01) than low MW (M=3378.59, SD=838.40), contrary to H1. The pairwise comparison of high and low MW individuals under sham condition revealed the largest numerical difference between means, M_{diff}= -604.46 ms, SE= 372.15, while under left stimulation condition there was little to no numerical difference, M_{diff}= 16.221, SE=462.30 (also see Figure 2). While post hoc comparisons did not yield significant results after Bonferroni correction, the pattern of means indicate that left tACS might have an equalizing effect.

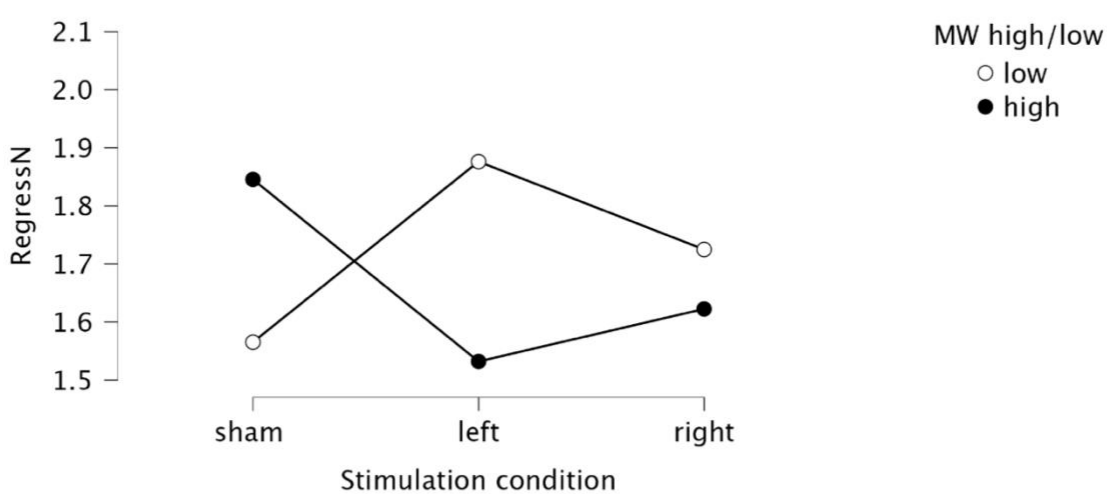
Hypothesis 2

The second hypothesis predicted that individuals with high MW would make less regressive saccades during right hemisphere alpha tACS compared to individuals with low MW.

Figure 3 below shows an interesting pattern, under sham condition high mind wanderers made more regressive saccades (M=1.85, SD=1.34) than low mind wanderers (M= 1.57, SD=.93). This pattern was reversed under the left stimulation condition, where high MW individuals had fewer regressions (M= 1.53, SD=1.02) than low MW individuals (M=1.88, SD= 1.19). Under right tACS the two group showed a smaller numerical difference (M_{diff}= .10, SE=.50).

Figure 3

Interaction of stimulation condition and MW level on regression number



We found no significant main effect of MW, after mixed ANOVA, $F(1,16) = .01$, $p = .92$. However, Mixed ANOVA found a significant interaction effect between stimulation condition and MW on regression number after correcting for sphericity violation with Greenhouse-Geisser correction ($\varepsilon = 0.75$), $F(1.50, 23.92) = 3.881$, $p = .046$, $\eta_p^2 = .195$. The main effect of stimulation was not significant for the second hypothesis as well, $F(1.495, 23.924) = .051$, $p = .908$, $\eta_p^2 = .003$). These results indicate that effect of stimulation on the number of regressions varied by mind wandering group.

It is important to note that none of the pairwise comparisons were statistically significant after Bonferroni correction, although the largest numerical difference was between low vs. high MW under left tACS, $M_{diff} = .34$, $SE = .17$. This finding does not support H2, which predicted fewer regressions for high MW individuals especially during right tACS.

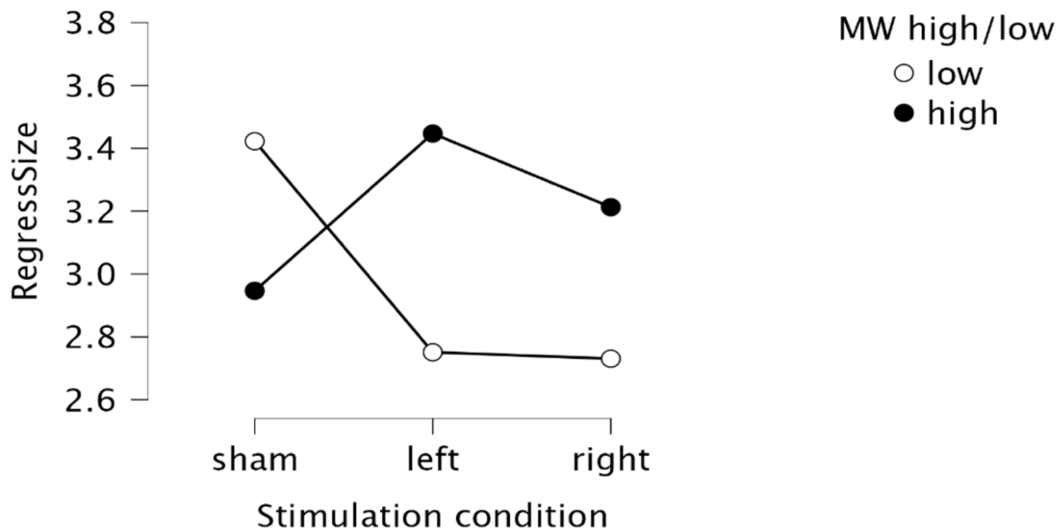
Hypothesis 3

The last hypothesis predicted that individuals with high MW would make larger regressions after right alpha-tACS compared to individuals with low MW.

As can be seen in Figure 4, in sham condition, high MW individuals made smaller regressions ($M = 2.95$, $SD = 1.07$) compared to low MW participants ($M = 3.42$, $SD = 1.09$). This numerical pattern was reversed in left and right tACS, where high MW individuals showed larger regression sizes, with especially striking numerical difference during left tACS.

Figure 4

Interaction of stimulation condition and MW level on regression size



We tested whether main effect of MW on regression size was statistically significant with mixed ANOVA. The results indicated that there was no significant main effect, $F(1,16)=.22$, $p=.65$. Therefore, as was the case with our other outcome variables, MW alone did not significantly influence regression size.

Mixed ANOVA showed a marginally significant interaction effect of stimulation condition and MW on regression size, $F\ (2, 32) = 3.29$, $p=.05$, $\eta_p^2 =.17$. The main effect of stimulation on regression was not significant, $F\ (2,32) = .39$, $p=.68$, $\eta_p^2 =.02$. Similarly to the findings of H2, these results could indicate that the effect of stimulation on regression size differs according to MW level.

Moreover, post-hoc pairwise comparisons highlight an interesting numerical trend, as the largest numerical difference was between low and high MW participants under left tACS with

M_{diff}= -.70, SE= .59. However, none of the MW group differences were statistically significant after Bonferroni correction.

Furthermore, although a statistically significant interaction effect was found, the direction was not consistent with H3, since while right tACS, improved reading for high MW group, it had a less pronounced difference (M_{diff}= - .48, SE= .62) compared to left tACS.

Summary of results

Findings show a consistent pattern across the three outcome variables (total reading time, regression number, regression size) suggesting that left hemisphere stimulation has a pronounced effect on reading in high MW individuals. While none of the three original hypotheses were supported in the expected direction, all the interaction effects are still statistically or marginally significant, with large effect sizes. Furthermore, although we had no hypotheses on the main effects of stimulation and MW, none of them was statistically (or numerically) significant.

We must note that post hoc pairwise comparisons revealed no statistically significant differences after correcting for multiple comparisons. However, the descriptive patterns (see Figure 2,3,4) and mean values indicate that left-tACS, improved the reading of high MW participants while impairing the reading of low MW participants. The expected beneficial role of right-tACS for high MW group was less pronounced or in the case of reading time, contrary to predictions.

Discussion

Overview of study & key results

In the present study (N=18), we investigated whether transcranial alternating stimulation (tACS) in the alpha band (10 Hz) modulates attention in reading and whether mind wandering tendencies moderate this effect of alpha tACS. Uniquely, we wanted to know for whom tACS is more effective for, specifically whether individuals who engage in mind wandering a lot would benefit more from the stimulation. On a broader scale, our study aimed to add on to previous work on the role of alpha oscillations in directing attention (e.g. Kasten et al.,2020; Kemmerer et al., 2022) by investigating eye movements in reading, a previously unexplored aspect. We evaluated reading performance through total reading time (ms), number of regressions (n) and regression size (degree). Previous work showed that shorter total reading time, lesser and smaller regressions are associated with improved reading (Wegger & Inhoff, 2009; Vitu & McConkie, 2000).

The results of our study support that alpha-tACS stimulation affects reading but only when we include mind wandering in the analysis. The main effects of stimulation, while not the focus of this paper, were all not significant. However, individual differences in mind wandering consistently influenced how individuals responded to the stimulation across every tested outcome variable. During stimulation on either hemisphere, high MW individuals take a shorter time to read, make less and shorter regressions. The opposite trend was found for low MW individuals after stimulation. Therefore, the findings indicate that tACS stimulation may improve reading but only in individuals who have difficulties in directing attention. As hypothesized, right tACS did led to fewer and larger regressions for high MW individuals, when compared to the sham condition. However, contrary to the initial hypotheses that right hemisphere alpha-tACS would enhance attentional control during reading, most pronounced modulation across all outcome variables was observed during left tACS.

Moreover, it is important to highlight the post hoc pairwise comparisons were not significant after Bonferroni correction likely due to limited statistical power resulting from the small sample size. However, we can still interpret the results as meaningful as the there is a consistent trend pointing to the modulating influence of tACS across the outcome measures. Below we discuss the theoretical and practical implications of the results.

Theoretical implications

The findings of our study, though limited in power, contribute to the work on the state dependent effects of non-invasive brain stimulation (Carrasco-Gomez et al., 2025; Martinez-Perez et al., 2022; Neuling et al., 2012; Wei et al., 2024). Considering that no main effects were detected, tACS may influence reading only under specific brain states, such as differing individual baseline alpha activity which includes their baseline alpha frequency, amplitude and phase. Previous literature on the effect of individual differences had found that the efficacy of alpha-tACS is often state-dependent as it varies as a function of baseline neural or cognitive states. For instance, Martinez-Perez et al. (2022) stated that alpha-tACS's influence on vigilance during tasks requiring sustained attention and inhibitory control was observed only under suboptimal arousal conditions. This may suggest that baseline alertness moderated tACS effectiveness. Similarly, Carrasco-Gomez et al. (2025) demonstrated that alpha-tACS was modulated functional connectivity patterns when administered at participants' individual alpha frequency (IAF), as measured by magnetoencephalography (MEG). Neuling et al. (2012) further demonstrated that the performance in auditory detection tasks depended on the baseline phase of alpha oscillations, measured by EEG, that was entrained by alpha transcranial direct current stimulation (tDCS). Although previous work did not focus on natural reading performance, they suggest that different components of baseline alpha activity such as frequency, amplitude and phase, may influence how tACS interacts with cognitive processes. Consequently, individuals with high MW tendencies might differ from individuals with low MW tendencies in terms of their baseline alpha characteristics. Alpha-tACS may be interacting with baseline alpha to amplify inhibitory control during natural reading. Individuals who are "less distractable" and therefore have low MW tendencies, likely remained in their optimal state and thus showed minimal or even adverse response to tACS.

Furthermore, our findings suggest a more complex role of alpha oscillations beyond lateralization models. The original hypotheses were based on the alpha lateralization theory's assumption that increased alpha amplitudes would reflect an inhibitory control mechanism (Peylo et al., 2021). Following Peylo et al. (2021), we had hypothesized that right hemisphere inhibition facilitates reading through ignoring the already processed words in the left visual hemifield. However, our results indicated otherwise as left alpha-tACS led to the greater improvement in natural reading, only in high mind wandering group. A possible explanation of this unexpected finding may be that brain temporarily suppresses preview of upcoming words, if they are not yet ready to be processed (Pan et al.,2023). During reading alpha might serve to prepare for upcoming input, and not only to ignore already processed words. It is important to also consider the potential interaction with MW tendencies. "Highly distractable" individuals could have more difficulties preparing for upcoming words rather than suppressing the previously processed words. Therefore, left alpha-tACS was particularly beneficial for individuals with high MW, who may struggle more with forward planning during reading. Thus, our findings do not contradict the lateralization hypothesis entirely, instead they offer a complementary perspective in which left hemisphere alpha facilitates reading in individuals who mind wander a lot, by supporting the temporal coordination of attention and processing for upcoming words.

Practical implications

The findings of our study can be put into practice in different ways. Firstly, since our findings supported the state-dependent effects of non-invasive brain stimulation, they can guide research towards developing interventions for specific groups of individuals, differing by their cognitive capabilities. This would be a step forward in the field of brain stimulation.

Most importantly, the results of our study can be utilized in a clinical setting to develop treatment for attention deficit disorder (ADD) and potentially dyslexia. Mind wandering tendencies may reflect attentional lapses, a core feature of ADD and it may serve as a trait level indication of attention disorders. Hence, neuromodulation can be used to train attention also in a subclinical population suffering from attention problems. Previous research on the clinical applications of tACS found evidence of the improvement of behavioral and cognitive symptoms, specifically for neurocognitive, psychotic and depressive disorders (Nezhad et al., 2024; Riddle et al., 2020). Long-term, repeated application of tACS has been highlighted as a crucial factor in improving symptoms. Riddle et al., (2020) found improved behavioral functioning after 5 consecutive days of alpha tACS. Currently, there is limited research specifically on the effectiveness of alpha-tACS on learning & attention disorders. Nonetheless, our findings suggest that an intervention can be designed, for individuals with ADD and dyslexia taking baseline alpha and the frequency of stimulation into account.

Limitations

This study has several limitations. The main limitation stems from the sham condition as 50% of all participants accurately guessed the order of the sham condition, as reported in the post-session questionnaire. This number increased to 60% in the high MW group. This could mean that participants were more distracted in the sham condition, compared to the stimulation conditions, as they were deliberating whether they are receiving any stimulation. This is particularly the case for high MW participants as they are more inclined to have task-unrelated thoughts than low MW participants (Mrazek et al., 2013). Therefore, worse performance in natural reading in the sham condition could be attributed to increased distractibility rather than lack of tACS modulation.

Another limitation is the lack of neuroimaging measures such as EEG, in our study. Since we did not record changes in alpha during stimulation, it is unclear whether tACS modulation of alpha amplitude was effective. Moreover, the baseline alpha amplitudes and IAFs of the participants were not measured. Most of previous research looking at individual differences and the state-dependent effects of tACS, took baseline alpha measures into account. Without these measures, we were unable to explore if tACS had different effects based on brain states.

Furthermore, a clear limitation is the small sample size (N=18) due to timing, financial and practical considerations. As previously mentioned, our small sample limited the statistical power, thus it was harder to detect stimulation effects. The limited power might explain why there was no main effect found and why the post-hoc comparisons of the interaction were not significant after the Bonferroni correction.

Future research

Based on the limitations stated above, future research on tACS's modulation of attention in reading can benefit from the inclusion of EEG recordings during and prior to stimulation. Monitoring brain activity during stimulation would strengthen the manipulation as real-time modulation of alpha oscillations would be visible in the recording. Furthermore, pre-stimulation EEG recordings could give insight into whether base alpha amplitude is a factor in stimulation effectivity. This is interesting as baseline alpha amplitude may reflect MW related individual differences in attention, making some individuals more responsive to stimulation. However, tACS is more effective when tailored to a person's IAF, as this makes optimal neural entrainment possible. A step further would be tailoring tACS frequency according to IAF to investigate if the differences between MW groups disappear when each group is stimulated at their optimal frequency and explore if baseline alpha amplitude plays any role in individuals' "susceptibility" to stimulation.

Moreover, future research can benefit from exploring the long-term effects of stimulation, as well as the effectiveness of consecutive daily or weekly tACS sessions in improving attention in reading among highly distractible individuals. Research on continued alpha-tACS administration found lasting improvement in depression symptoms in a clinical sample (Riddle et al., 2020). However, the effects of consecutive alpha-tACS are not yet known for attention deficits in subclinical population. Hence, future research can focus on subclinical trials of continued alpha-tACS treatment of attention and learning disorders such as ADD and dyslexia.

Finally, since our findings might indicate that alpha oscillations in the left hemisphere play a role in forward planning during reading, future research can include follow-up experiments to test the new hypothesis. To test this, follow-up experiments can use the boundary paradigm, a gaze-contingent method where a preview word is shown before the target which disappears once the gaze crosses an invisible boundary (Rayner, 1975). The preview is either a "valid" word which is identical to the target word or an "invalid" word which is a non-word. Shorter fixation duration on the target word in valid trials would then reflect greater preview benefit and thus, better planning for the upcoming word. Considering this theoretical background a new research questions can be posed "Does left alpha-tACS improve preview benefit during reading by facilitating saccadic planning?" and "Do individuals with high MW tendencies experience greater preview benefit during left alpha-tACS?"

Conclusion.

This study aimed to explore whether alpha-tACS modulates attention in reading and for whom it is most effective. Our findings suggested no main effect of stimulation but showed a consistent interaction with mind wandering tendencies across outcome variables. Although post hoc comparisons were not significant after correction, the pattern suggests a meaningful effect, especially for high MW individuals. Contrary to traditional alpha lateralization theories, the strongest modulation occurred during left tACS. Overall, our findings contribute to the understanding of individual differences in tACS responsiveness and point toward the importance of state-dependent brain stimulation in attention and reading research.

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Appendix

Descriptive statistics for each dependent variable across the six experimental conditions (3 stimulation × 2 mind wandering groups)

Stimulation condition x MW	Total reading time (ms)	Regressive saccades (n)	Regression size (visual angle)
Right tACS x high MW	3557.75 (931.01)	1.62 (0.97)	3.21 (1.48)
Right tACS x low MW	3378.59 (838.40)	1.73 (1.15)	2.73 (1.06)
Left tACS x high MW	3447.84 (1121.78)	1.53 (1.02)	2.95 (1.07)
Left tACS x low MW	3464.07 (743.76)	1.88 (1.19)	3.42 (1.09)
Sham x high MW	3746.98 (901.17)	1.85 (1.34)	3.45 (1.42)
Sham x low mW	3142.52 (602.32)	1.57 (0.93)	2.75 (0.97)

Note. Values are means, with standard deviations in parentheses.