Neuromodulation of Attention in Reading

The Effect of Alpha Transcranial Alternating Current Stimulation on Eye Movement Rhythmicity

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Abstract

Alpha-band neural oscillations (8–12 Hz) have been implicated in attentional control and eye movement timing during reading. Recent evidence suggests saccadic eye movements may align with the phase of alpha oscillations, particularly in the right parietal-occipital cortex. This study investigated whether transcranial alternating current stimulation (tACS) at alpha frequency can enhance the rhythmicity of eye movements during natural reading. Eighteen participants read sentences while receiving either left, right, or sham alpha-tACS in a within-subjects design. Eye movement rhythmicity was operationalized as the coefficient of variation (CV) of first fixation durations (FFDs). While the study replicated the expected slowing effect of the moving window paradigm, alpha-tACS did not significantly alter FFD variability compared to sham. The results suggest that fixed-frequency alpha-tACS does not reliably modulate eye movement rhythmicity in reading tasks. Potential explanations include insufficient stimulation intensity, lack of frequency individualization, or strong intrinsic alpha entrainment during reading. These findings emphasize the need for individualized stimulation protocols and highlight the complex interaction between neuromodulation and cognitive processes.

Keywords: transcranial alternating current stimulation (tACS), natural reading, alpha oscillations, eye movement rhythmicity, visuospatial attention

The Effect of Alpha Transcranial Alternating Current Stimulation on Eye Movement Rhythmicity

The rhythmic nature of brain activity, particularly in the alpha frequency band (8-12 Hz), has been implicated in various cognitive processes, including attention, working memory, and sensory processing (Klimesch, 2012). Studies have shown the role of these alpha oscillations in visuospatial attention as well, showing how increases and decreases in alpha power relates to directing visuospatial attention towards specific cues (Sauseng et al., 2005). This begs the question: Is there a link between alpha oscillations and attentional direction, through what underlying mechanisms does it work and can they be influenced?

Perhaps the most common example of directing visuospatial attention is found in the everyday activity of reading. Reading, the processing of textual information to recover its intended meaning, is perhaps more complicated than it sounds. Even when the motor cognitive process itself goes smoothly text can be ambiguous or confusing, sometimes requiring we take a step back and reread a sentence, or an entire chapter. And though most authors write with the aim of being understood by their readers, more often than not reading requires conscientious effort and directed attention. But what guides that attention, and the associated motor functions, such as eye movements, with it?

Eye movements, characterized by alternating fixations and saccades, are fundamental to the reading process. Fixations allow for the extraction of visual information, while saccades facilitate the shifting of gaze to subsequent words (Rayner, 2009). Research has shown a potential link between the alpha oscillations mentioned before and the temporal dynamics of eye movements during reading. Henderson et al. (2018) investigated the neural correlates of individual differences regarding fixation durations during natural reading. They found that increasing neural activity in specific regions associated with cortical eye movement lowered the interpersonal variability and skew of fixation durations across individuals, suggesting that specific neural activity such as alpha oscillations are associated with specific eye movement, and could be closely related to language processing. Pan et al. (2023) recently provided even more evidence that saccades are not only associated with alpha oscillations, but are locked to specific phases of alpha oscillations during natural reading, strengthening the proposed link between alpha rhythmicity and eye movement timing. This study also found that the alpha oscillations seemingly responsible for this timing mechanism were mostly found in the right hemisphere of the visual motor cortex. The right hemisphere has also been noted as an important area when it comes to visuospatial processing and attentional control by a study by Corbetta & Shulman (2002). These findings were further collaborated in a study by Kornrumpf et al. (2017). They demonstrated that lateralization of posterior alpha EEG reflects the distribution of spatial attention during saccadic reading, indicating a link between alpha activity and the control of eye movements, giving more credence to hemispheric differences in the realm of attentional control during reading. Seeing that alpha oscillations, especially in the right hemisphere, are proposed to be closely related to visuospatial attentional control and eye movement, leads us into the following question: Can these alpha oscillations be influenced in order to influence eye movement?

Transcranial alternating current stimulation (tACS) offers a non-invasive method to modulate brain oscillations, specifically in the alpha frequency range (Herrmann et al., 2013). According to (Wischnewski et al., 2023), who provide a comprehensive overview of the neurocognitive, physiological, and biophysical effects of tACS, tACS has proven to be able to entrain endogenous brain rhythms and influence cognitive functions by modifying neural oscillations. By stimulating the scalp with specific frequencies of an alternating current, one can lower the threshold for neural activation and increase spike activity. While tACS cannot induce action potential on its own, it can guide and organize neural activity to more closely follow the external frequency, especially if the provided frequency aligns with an already present intrinsic neural oscillation frequency. While previous studies have explored the effects of alpha-tACS on various cognitive domains, one area that has remained largely unexplored is its influence on the rhythmicity of eye movements during reading, and whether they are related to alpha oscillations.

This study therefore aims to investigate the effects of alpha-tACS on the rhythmicity of eye movements during natural reading tasks. Specifically, we hypothesize that right hemisphere alpha-tACS will increase the rhythmicity of eye movements, as evidenced by reduced variability in first fixation duration. We plan to investigate the effects of right alpha-tACS on eye movement rhythmicity during natural reading when compared to left alpha-tACS and a sham stimulation. By examining these effects, we hope to contribute to a deeper understanding of the relationship between alpha oscillations, hemispheric specialization, and the temporal dynamics of eye movements during natural reading.

Methods

Participants

Participants for the study were gathered through convenience sampling. Researchers invited friends and fellow students to participate in the study. Students were also asked to participate through the SONA program at the Rijksuniversiteit Groningen (RUG), a program attached to a first-year course in the Psychology bachelor program at the RUG. Students are asked to participate in studies registered with SONA in return for course credits, regardless of whether their collected data was used or useable. Through these methods, a group of 20 participants was gathered to participate in the study. Of these participants, two were excluded because no useable data could be collected from them because of difficulties with eye-tracking, participants meeting exclusion criteria such as skin conditions on the scalp or participants having difficulty reading the task screen without glasses. After these exclusions, the data of 18 participants (ages 19-29, *M* = 21.5 years, *SD* = 2.04 years; 13 women) was used in this study. One of the participants indicated English is their first language, the other 17 participants were non-native English speakers. According to the Edinburgh Handedness Inventory (Oldfield, 1971), 16 participants were right-handed and two were left-handed. Procedures involving the participants have been approved by the RUG Ethics Committee (study code: PSY-2425-S-0301), and participants all provided written informed consent before participating in the experiment.

Task

Participants were asked to sit in front of a screen with their heads in a headrest to stabilize them for eye-tracking purposes. While wearing an EEG cap to hold the alpha-tACS electrodes in place, they were asked to read an English sentence at their own pace. During each trial (consisting of one sentence), participants started by focusing on a small black dot near the left side of the screen. Afterwards, a full English sentence was shown. Participants were asked to read each sentence at their own pace and then look at a small black dot on the right side of the screen to finish reading. This then triggered the start of the next trial, creating a natural left-to-right reading flow. After 33.34% of the sentences, a simple yes or no question about the preceding sentence would appear, which the participant would then answer using the mouse buttons. They were shown when they answered the wrong answer, although incorrect responses had no other consequence. Which 33.34% of the sentences was followed by a question was randomized. Participants were asked to read three blocks of 60 sentences like this, totalling 180 sentences.

Sentence materials

Sentences were pulled from a text corpus compiled by Frank et al. (2013), also known as the UCL corpus. This corpus consists of 361 English sentences pulled from amateur novels available online. From these 361 sentences, we selected 201 sentences for our study. Sentences were selected based on character length (maximum length of 100 characters), readability and non-violent content, as some of the sentences contained more graphic material than others. Each selected sentence was coupled with a yes or no question regarding that sentence, either provided by the corpus or added by us. 110 of the selected sentences were used with the provided questions, 91 sentences were used with questions added or altered by us, to ensure a balanced amount of yes/no answers.

Design

Two factors were manipulated on a within-subject basis: stimulation condition and moving window condition. Stimulation condition had three levels: sham, left and right stimulation. During each of the three reading blocks, participants received a random counterbalanced stimulation condition to prevent order effects. Counterbalancing was done through the use of a Latin square. When a participant received the sham condition, the electrodes of the same side preceding it were used, or when the sham condition came first, the electrodes of the same side of the condition succeeding it were used. The moving window condition had two levels: natural reading and moving window. During each reading block of 60 sentences, the participant was given 30 sentences in the natural reading condition and 30 sentences in the moving window condition. Sentences in the moving window condition were obstructed, replacing all letters except for the four letters to the right of the participant’s current fixation point by the lowercase letter ‘x’, maintaining visible spaces between words. Which 30 sentences were provided in the moving window condition was randomized.

Procedure

Participants were first given an information sheet about the study and asked to fill out an informed consent form. Afterwards, they were given a short questionnaire detailing demographic information such as age and gender, and their experience with the English language. After the questionnaire, participants were asked to sit in front of a computer screen where the reading task would be displayed, and checked for any difficulties in tracking their eye movements. This was done by calibrating the eye-tracker, and asking the participant to follow a researcher's finger around the edges of the screen while checking whether the eye-tracker could keep track of the participants' eye in every position. After this preliminary check, four tACS electrodes were applied to the participants' scalp over occipital-parietal cortex areas (two electrodes on each hemisphere). After the electrodes were applied, a short trial stimulation was applied to check whether the stimulator worked properly on the participant. The trial stimulation was set to 0.750 mA at 10 Hz, half power of the full stimulation of 1.5 mA at ten Hz used during the reading task. The trial stimulation would linearly ramp up to 0.750 mA over 30 seconds, after which the stimulation was continued for 30 more seconds. The participant was asked about any uncomfortable sensations, and whether they found the stimulation distracting. The stimulation was then turned off manually. After the trial stimulation, participants were placed back in front of the computer screen and asked to rest their head in an eye-tracking headrest placed in front of the screen. The eye-tracker was then calibrated using a nine-point calibration and validation test.

Participants were then asked to complete a natural reading task, where they read one-line English sentences in three blocks of 60 trails. During the reading task, 33.34% of sentences were randomly followed up by a comprehension question which the participants had to answer (yes or no) using the mouse buttons. In each reading block of 60 trials, half of the trials included a gaze-contingent moving window condition. At the end of the third reading block, participants were informed the experiment had finished, and the electrodes were then removed from their scalps.

After the experiment, participants were asked to fill out a few questionnaires. These questionnaires consisted of the Edinburgh Handedness Inventory (Oldfield, 1971), a short post session questionnaire asking about their experience and whether they could tell which condition was the sham condition, a standardized questionnaire about the vividness of their visual imagery and a short standardized questionnaire about their general propensity for mind-wandering. The vividness of visual imagery questionnaire consisted of 16 descriptions of varying scenarios the participant had to visualize. They would then rate their visualization on a five-point Likert scale ranging from '1: No image at all' to '5: Perfectly clear and lively as real seeing.' The mind-wandering questionnaire consisted of five questions on mind-wandering tendencies, such as: 'I have difficulty maintaining focus on simple or repetitive work.' Participants were asked to answer each question on a six-point Likert scale ranging from '1: Almost never.' To '6: Almost always.' Participants were then also given the option to ask any additional questions they had about the experiment.

Apparatus

The eye-tracker used was the Eyelink 1000 Plus manufactured by SR Research. For the alpha-tACS, four tACS electrodes were applied to the participants' scalp over occipital-parietal cortex areas (two electrodes on each hemisphere). The electrodes were connected to an Eldith DC-Stimulator manufactured by NeuroConn. Standard EEG gel was used to aid with conduction between the electrodes and the scalp.

Eye-tracking

The participants were sat at a desk with their heads in a headrest standing 73.5 cm from the screen. The screen that displayed the sentence materials was a TN-panel with a resolution of 1920 x 1080 pixels and a vertical refresh rate of 120 Hz. The characters on screen were 13 pixels wide, corresponding to a width of 0.32° of visual angle per character at the viewing distance of 73.5 cm. The accepted eye-tracking error during calibration was one visual degree for each calibration point, and a maximum average error of 0.50° was deemed useable. The x and y position of the right eye and the pupil size were acquired at a sampling rate of 1000 Hz. Fixation detection was based on the Eyelink online detection algorithm. Saccade detection was set at a velocity threshold of 30° per second, along with a saccade acceleration threshold of 8000° per second.

Data preprocessing

The raw eye-tracking data was converted to ASCII text files using the eye-tracker manufacturer's accompanying software suite. The raw data was then processed using a Matlab preprocessing script. Trials were excluded if they contained more than two blink events. Saccades and fixations were also removed from the data if their beginning or end was closer than 50 ms to any blink events.

Results

Task performance

Overall, participants showed a high accuracy on the reading task questions (*M* = 88.3%, SD = 7.6 across all conditions), indicating they generally understood the sentences well and were able to answer most questions correctly. A RM-ANOVA analyses of the different stimulation conditions showed no significant difference in accuracy between the stimulation conditions, $F(2, 34) = 0.365$, $p = .697$. Accuracy was comparable in the left (*M* = 89.6%, *SD* = 9.2) and right (*M* = 88.0%, *SD* = 10.3) stimulation conditions compared to the sham condition (*M* = 87.3%, *SD* = 10.7). In terms of total reading time, participants again performed comparable in left (*M* = 3.93 s, *SD* = 1.03 s), right (*M* = 4.00 s, *SD* = 0.93 s) and sham (*M* = 4.04 s, *SD* = 0.99 s). A RM-ANOVA analyses also showed the difference in total reading time between stimulation conditions was not significant, $F(2, 34) = 0.332$, p =0.720.

Effect of moving window paradigm on reading

In order to check the experimental setup of the reading task, a moving window condition was added to the reading task. Since the moving window paradigm, the attentional preview benefit of preprocessing words slightly ahead of our current reading position, has been replicated numerous times in comparable eye-tracking studies since the first experiments showing evidence for this paradigm by McConkie & Rayner (1975, 1976), this effect should then also be present in our data. When comparing the natural reading condition to the moving window condition, participants were shown to read significantly faster in the natural reading condition, $t(17) = -11.546$, $p < .001$. When aggregated across all stimulation conditions, participant read the provided sentences faster during natural reading (*M* = 3.47 s, *SD* = 0.83 s) than they did in the moving window condition (*M* = 4.48 s, *SD* = 1.04 s). These differences were also visible within each stimulation condition separately, where participants read significantly faster during natural reading in both the sham ($t(17) = -7.689$, $p <.001$), left ($t(17) = -8.468$, $p < .001$) and right ($t(17) = -6.374$, $p < .001$) stimulation conditions. Thus, this study was also able to replicate the moving window paradigm.

Effect of stimulation condition on fixation rhythmicity

To test our hypothesis, we have chosen to operationalize increased rhythmicity of eye movement as a decrease in the coefficient of variation (CV) for first fixation durations (FFDs). Furthermore, the choice was made to only focus on performance in the natural reading condition of the reading task, as natural reading has been most closely related to the locking of saccadic movement to alpha oscillations (Pan et al., 2023). Table 1 shows a summary of descriptive statistics for the FFD in all stimulation conditions during the natural reading trials. Here we see that, at first glance, the mean FFD is quite similar across stimulation conditions, while the SD is slightly higher for both left and right stimulation when compared to the sham condition.

Table 1

Descriptive Statistics

	FFD_sham_natural	FFD_left_natural	FFD_right_natural
Valid	18	18	18
Missing	0	0	0
Mean	220.675	220.987	222.857
Std. Deviation	27.808	32.576	31.045
Minimum	172.063	168.473	168.787
Maximum	267.347	285.561	277.695

Table 2 shows a summary of descriptive statistics for the FFD CV across all stimulation conditions. FFD CV was marginally lower in both the left and right stimulation condition when compared to sham, although a RM-ANOVA shows there was no significant difference between stimulation conditions, $F(2, 34) = 0.525$, $p = 0.596$. Noticeably, the mean CV for both left and right stimulation was the same, suggesting that whatever non-significant effect the stimulation might have had on eye movement rhythmicity was similar in both stimulation conditions. Figure 1 shows raincloud plots comparing the data of each stimulation condition to each other, again showing no significant differences in CV. What does stand out in these graphs, is that both left and right stimulation conditions appear to broaden the range of CV among participants when compared to the sham condition. This effect appears to be most prominent during left side stimulation, suggesting a higher degree of individual difference in response to the left stimulation. However, when looking back to our original hypothesis, we have to conclude it is rejected based on this study, as there appears to be no significant increase in rhythmicity of eye movement.

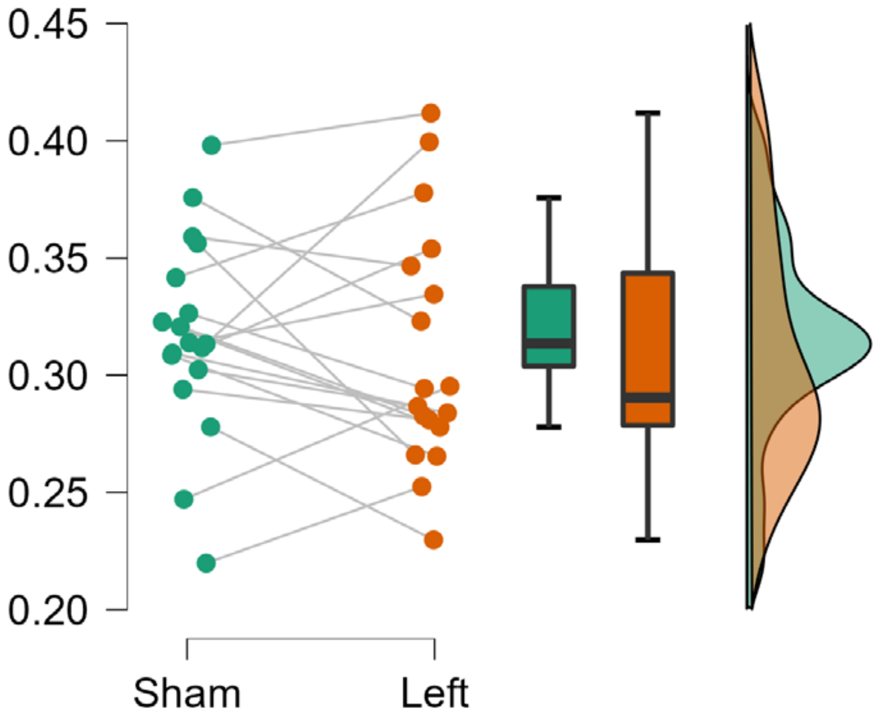
Table 2

Descriptive Statistics

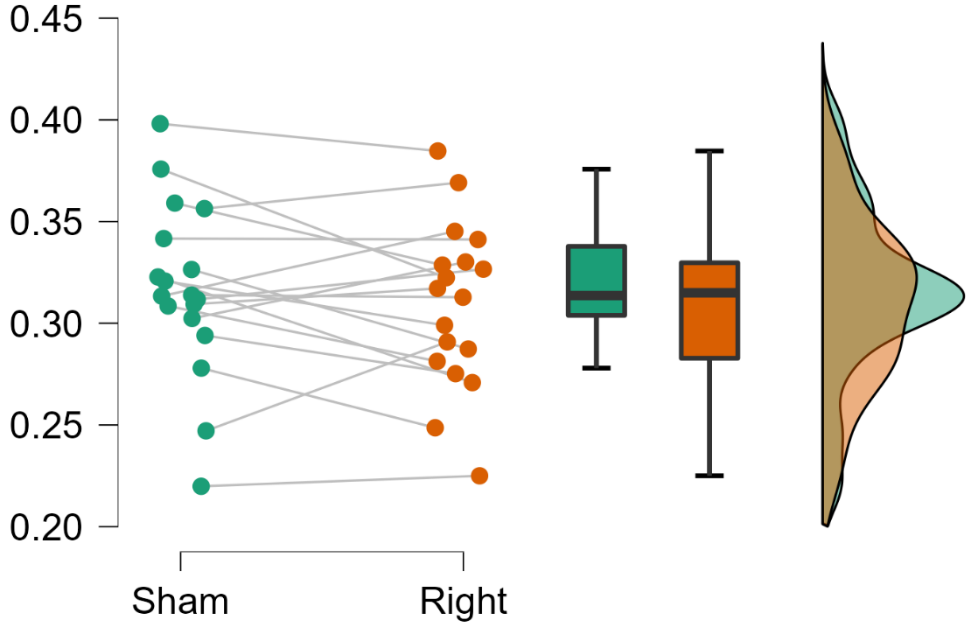
	CV_FFD_sham_natural	CV_FFD_left_natural	CV_FFD_right_natural
Valid	18	18	18
Missing	0	0	0
Mean	0.317	0.309	0.309
Std. Deviation	0.043	0.051	0.041
Minimum	0.220	0.230	0.225
Maximum	0.398	0.412	0.385

Figure 1

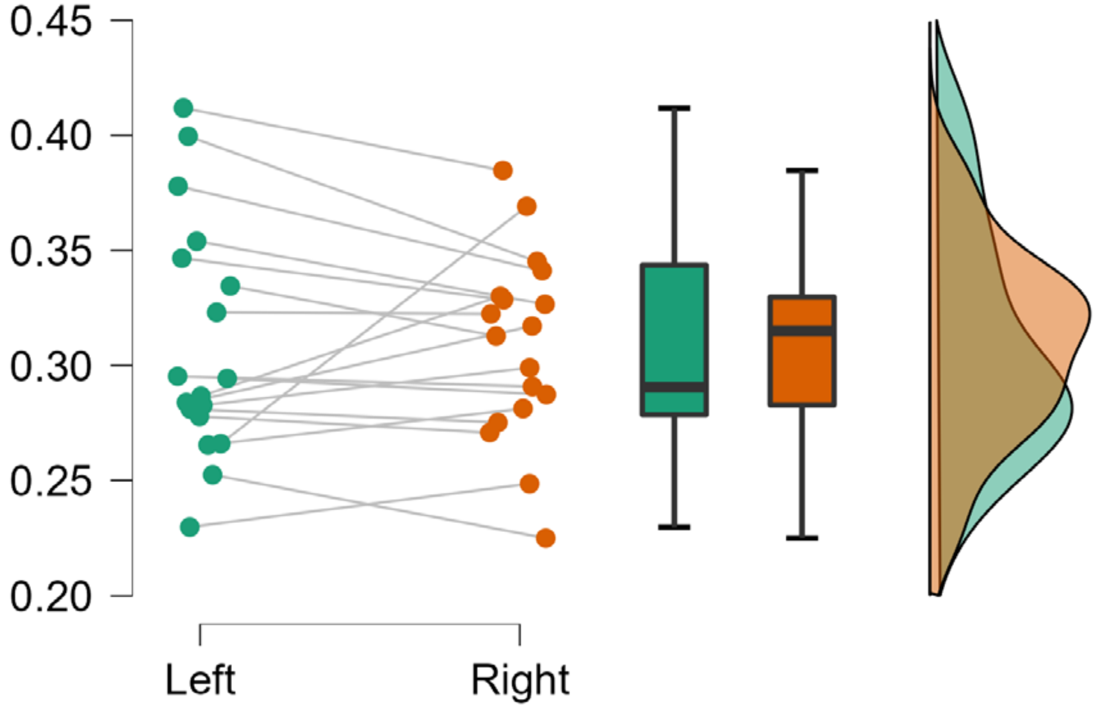
CV_FFD_sham_natural - CV_FFD_left_natural



CV_FFD_sham_natural - CV_FFD_right_natural



CV_FFD_left_natural - CV_FFD_right_natural



Discussion

The aim of this study was to investigate whether alpha-tACS is able to influence the rhythmicity of eye movement by decreasing the variability of first fixation durations. The effects of alpha-tACS were examined through an experimental research design where participants were asked to perform a reading task while an eye-tracker tracked their eye movements. During this task the participants received alpha-tACS stimulation on either the left or right hemisphere of the parietal-occipital region, or a sham stimulation. Our hypothesis, that right side alpha-tACS would increase rhythmicity of eye movement by decreasing the variability of first fixation durations, was rejected based on the results of this study.

There was no significant effect of alpha-tACS on first fixation duration variability, as operationalized through the coefficient of variation. This implies that alpha-tACS has no or a very small effect on the temporal locking of saccades to alpha oscillations, as demonstrated by Pan et al. (2023). A possible explanation could be that the added alpha power in the stimulated region is relatively minor compared to the natural laterization of alpha oscillations occurring during natural reading (Kornrumpf et al., 2017). This might imply for example that the locking of saccadic movements to the alpha oscillations has a relatively low threshold to occur during attentional tasks such as reading, where the relatively minor added effect of tACS has no added benefit. Another possible explanation might be found in the individual differences in naturally occurring alpha oscillation frequency. As demonstrated by Huang et al. (2021), tACS best entrains alpha oscillations by following the so-called Arnold tongue, meaning the closer the frequency match between intrinsic and external oscillations, the better the following entrainment will be. By stimulating every participant with a generic 10 Hz alpha frequency instead of trying to match the stimulation to the naturally occurring peak frequency in alpha oscillations in each individual participant, the effects of tACS might be lessened. Other studies have shown examples of tACS actually hampering intrinsic rhythmic neural oscillations by competing with the brain's ongoing oscillations (Krause et al., 2022). Perhaps future studies might be aimed towards examining whether individually calibrating the optimal stimulation frequency per participant yields better results.

Limitations

An obvious limitation of the current study was the small pool of participants, with only 18 participants. Considering the generally small effect size of tACS manipulation (Wischnewski et al., 2023), a high-powered study would be needed to find significant effects from tACS manipulations. A larger participant pool would increase statistical power, and therefore lend more credibility to the results found. Another potential issue with the experimental design of the study was the failure of the single blind design, where participants were not supposed to know the stimulation condition per reading block. In the post-session questionnaire, nine (50%) of the participants were able to correctly specify during which reading block they received the sham stimulation, indicating the difference was noticeable for participants. This might have caused participants to behave or perform differently from how they would have behaved or performed in a true single blind experiment. Future studies might have to devise another way of conducting a sham manipulation that is less distinguishable from the 'real' manipulation conditions, although the associated physiological sensations that are caused by tACS might render that difficult.

Implications and future research

As mentioned earlier, the results of the current study would imply that localized alpha-tACS is not suitable to significantly influence the relation between alpha oscillations and eye movement. These results lend further credibility to the Arnold tongue phenomenology, suggesting specific individual finetuning is required for tACS to perform with adequate efficacy when trying to influence cognitive processes, especially ones that already involve a high degree of attentional direction resulting in intrinsic alpha laterization (Kornrumpf et al., 2017). Other studies have shown the contextual effect of tACS can differ significantly based on individual and task-specific differences like brain-state (Nguyen et al., 2018) or even specific electrode placement based on individual variability in induced intracranial electric fields (Opitz et al., 2018). More research is clearly needed to hone in on precise manners of finetuning tACS to each individual in order to maximize its effects.

This study could also have implications with regard to the inhibition timing hypothesis (Klimesch et al., 2007) and associated inhibition gating theory (Jensen & Mazaheri, 2010). These theories propose a timing and routing mechanism facilitated through alpha oscillations in specific brain regions, differing in amplitude to inhibit specific irrelevant regions and pathways and timing parallel processes through inhibition of ‘on-hold’ information processing. Since alpha-tACS has been shown to increase intrinsic alpha oscillation amplitude (Kasten et al., 2020) and increased alpha amplitude is associated with the inhibitory mechanisms proposed by these theories, one would assume alpha-tACS should affect these gating and timing mechanisms, possibly including our hypothesized increase in rhythmicity. Since the data did not support our hypothesis, future research could be aimed towards developing further understanding of the role alpha oscillations play in inhibitory gating and timing mechanisms, and their proposed link to eye movement timing.

Furthermore, since our study was relatively conservative when it came to the stimulation current (1.5 mA), future studies might be able to investigate the effects of similar experiments using higher currents. Research has shown that currents up to 4 mA are safely useable in human research (Khadka et al., 2020) and that effects of tACS are more pronounced at higher intensities (Johnson et al., 2020). Future research could be conducted into the effects of similar tACS manipulations using slightly higher frequencies.

Conclusion

The aim of this study was to answer the following question: Can eye movement rhythmicity be affected by alpha transcranial alternating current stimulation? Based on our findings there was no significant effect of alpha-tACS on eye movement rhythmicity, as operationalized through the coefficient of variation of first fixation durations. These findings add to existing research surrounding the effects of alpha-tACS on the cognitive process by providing further support for theories such as the occurrence of Arnold tongue phenomenology in neural oscillations. This study also confirmed existing finding within eye-tracking research by replicating the effect of the moving window paradigm. Looking ahead, this study provides various avenues for future research, such as the benefits of more specific finetuning of alpha-tACS to individual participants, the underlying mechanisms of proposed inhibitory gating and timing through alpha oscillations and the benefits of increased stimulation currents in tACS. It is through these avenues this study contributes to a deeper understanding of underlying neural cognitive processes, and provides a window into future research into ways to influence these processes, hoping to give way to new clinical interventions and treatment methods for neurological disorders and pathologies.

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