The Effects of Transcranial Alternating Current Stimulation (tACS) Over the Occipito-Parietal Cortex on Visuospatial Attention

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Abstract

Multiple brain mechanisms regulate visuospatial attention, one of the many cognitive processes in which neural oscillations are essential. Alpha-range oscillations (7–13 Hz) have repeatedly been found to decrease during periods of increased attention. Researchers have used transcranial alternating current stimulation (tACS), a non-invasive neurostimulation technique aimed to modulate the rhythmicity of brain activity, to explore causal relationships between oscillations and cognition. The current thesis aims to present a conceptual replication study aimed at replicating previous findings that alpha tACS applied to the left or right occipito-parietal cortex reduces visuospatial attention in the contralateral hemifield. It was hypothesised that independent of cue validity, applying tACS would result in slower reaction times and lower accuracy in the ipsilateral hemifield. Additionally, it was expected that valid trials, regardless of stimulation, would result in faster reaction times and higher accuracy compared to invalid trials. 11 participants completed a Posner visuospatial attention task during three experimental conditions: left, right, and sham tACS. The hypothesis concerning validity and reaction times was confirmed, further supporting decades of research validating the Posner task. However, no significant effects of tACS were found, consistent with previous null findings. Several factors may explain this, including individual variability, lack of phase alignment, or insufficient stimulation intensity. A previously unanticipated result showed that cues on the left hemifield resulted in slower reaction times compared to those in the right hemifield. The finding broadly supports the idea that visuospatial attention might be biased toward the left visual field. Nevertheless, as this is an interim analysis, the full project may yield different results, and a larger sample will be needed to confirm these preliminary findings.

Keywords: transcranial alternating current stimulation (tACS), neural oscillations, alpha rhythms, visuospatial attention, endogenous attention

The Effects of Transcranial Alternating Current Stimulation (tACS) Over the Occipito-Parietal Cortex on Visuospatial Attention

Playing ‘I spy’ as a little kid encouraged us to focus on specific objects in our environment to win the game. Meticulously scanning our surroundings to find the specified things and spotting them first was essential for winning. The game underscores the ability to select a visual space where the processing of stimuli is enhanced. This phenomenon is known as visuospatial attention (Posner, 1980). This preferential processing of relevant stimuli, while ignoring the irrelevant ones, enhances focus and orientation in the environment (Kemmerer et al., 2022a).

Attention can be distinguished in various ways, for example, overt versus covert, and exogenous versus endogenous attention. Overt visual attention encompasses physically directing the eyes to selectively process a stimulus, whereas covert visual attention refers to only a mental shift in attention without redirecting the eyes which helps to simultaneously process multiple locations (Rai & Callet, 2018). Exogenous attention is stimulus-driven and refers to a type of processing that is automatic and guided by the properties of the stimulus itself, such as colour, motion, or location; while endogenous attention is more goal-driven and refers to directing attention based on current goals or prior knowledge (Kemmerer et al., 2022a; Silas et al., 2023; MacLean et al., 2009). Both covert endogenous and exogenous spatial attention can aid visual perception; however, in some controlled experimental settings, endogenous attention may enhance perception, whereas exogenous attention can sometimes hinder it (Fernandes et al., 2021). A study by Turgut et al. (2021) showed that neglect patients who practiced an endogenous visuospatial attention task experienced significant improvements, whereas those who practiced an exogenous task did not.

Neural oscillations are a form of brain activity that is related to attention allocation. They are rhythmic patterns of activity that occur across various frequency bands and brain regions, and have been linked to a range of cognitive functions (Nyhus & Curran, 2010). Alpha rhythms (7-13 Hz) are related to many psychological processes, including perception and purposeful movement, and they play a causal role in visuospatial attention (Kora et al., 2021; Dustman & Beck, 1965). Shifting attention is linked to modulations in alpha power over the parietal and occipital regions, characterized by increased alpha activity in the hemisphere ipsilateral to the attended location relative to the contralateral hemisphere, which is known as interhemispheric asymmetry (Händel et al., 2011; Schuhmann et al., 2019; Kasten et al., 2020; Thut et al., 2006).

It is assumed that alpha oscillations serve as an attentional inhibition mechanism, allowing for the selective processing of stimuli by suppressing distracting sensory input (Kemmerer et al., 2022b). The modulation of alpha in relation to visual awareness is demonstrated in multiple studies, showing that the amplitude of alpha power at the time of stimulus presentation predicts whether the stimulus will be consciously processed or not (Romei et al., 2010; Harris et al., 2018). This effect is specific to the parieto-occipital regions, thus when alpha power decreases, the area becomes disinhibited. This reduction is often seen when attention is actively directed toward a stimulus and when stimuli are consciously perceived. In contrast, an increase in alpha power is thought to reflect functional inhibition of the underlying region, particularly for unattended or irrelevant stimuli, potentially allowing the selective suppression of such information. (Hutchinson et al., 2020; Sadaghiani & Kleinschmidt, 2016).

The findings on how alpha oscillations affect attention is still inconsistent (Van Diepen et al., 2019; Foster & Awh, 2019). However, there are various neuromodulation techniques that can modulate alpha waves non-invasively, allowing to investigate potential causal relationships. One non-invasive modulation technique is transcranial alternating current stimulation (tACS), that holds significant potential for cognitive research and can modulate cognitive functions (Wischnewski et al., 2023). tACS has been used to modulate oscillations and to explore causality in the brain-behaviour relationship (Coldea et al., 2021). It works by generating oscillatory electric fields that alter neural spike timing, resulting in changes in local neural oscillatory power (Wischnewski et al., 2023).

In one study by Hutchinson et al. (2020), researchers explored the role of alpha oscillations in inattentional blindness, a phenomenon where individuals fail to notice clearly visible but unexpected stimuli due to their attention being occupied by another demanding task (Most et al., 2005). Using tACS, the researchers applied alpha (11 Hz) theta (5 Hz) and sham stimulations over the occipital cortex while participants identified target stimuli within a visual array as an unexpected stimulus occasionally appeared. Those receiving alpha stimulation were less likely to perceive the critical stimulus compared to the other groups. The results support the theory that alpha oscillations act as a cortical inhibition mechanism, gating visual information and reducing awareness of task-irrelevant stimuli (Hutchinson et al., 2020).

Kemmerer et al. (2022a) applied tACS during both endogenous and exogenous visuospatial attention tasks to assess behavioural visuospatial attention bias. While dorsal parietal alpha-tACS failed to show an effect on exogenous attention, behavioural data revealed that tACS could induce a bias in endogenous attention, meaning a systematic shift in voluntarily directed attention toward the same side as the stimulation. Moreover, left parietal tACS enhanced a bias toward the left visual field, reflected by higher scores in accuracy and faster reaction times compared to right parietal stimulation, during the endogenous attention task, after correcting for sham effects.

Despite promising findings, not all studies replicate such results. Evidence for the lack of tACS effects was found in a study by Coldea et al. (2021), where they attempted to modulate alpha frequencies. The aim was to replicate previous findings suggesting that lateralized tACS would induce a shift in attention bias toward the ipsilateral visual hemifield and away from the contralateral hemifield. However, they found no significant difference between the sham condition and 10 Hz tACS (Coldea et al., 2021).

Given the inconsistencies across studies, concerns have arisen regarding the replicability of tACS-related effects. The current paper aims to present a conceptual replication study aiming to replicate the finding that alpha tACS applied to the left or right occipito-parietal cortex reduces visuospatial attention in the contralateral hemifield. Six hypotheses will be investigated throughout this thesis. Namely, whether, independent of the validity of the cues, applying tACS to the left or right occipito-parietal cortex will result in lower accuracy and slower reaction times in the ipsilateral hemifield. Moreover, it is hypothesised that in the invalid trials, reaction times will be slower, and accuracy will be lower compared to valid trials.

Methods

The thesis was preregistered at aspredicted.org (https://aspredicted.org/3x5t-8cf8.pdf), including the hypotheses, experimental design, and planned analyses.

Participants

In total, 12 participants were recruited from personal networks of the researchers. All participants received the research information prior to data collection, based on which they could decide to give informed consent for participation. There were several exclusion criteria: no neurological or psychiatric diseases, no memory-related diseases, no skin diseases, no history of epileptic episodes, no tattoo or piercing at the scalp, no metallic plates in the head or any kind of stimulators in the whole body. Furthermore, corrected-to-normal vision was necessary, but only contact lenses were allowed, as they did not interfere with the eye tracker device. One participant was excluded from the study for not completing all three stimulation conditions. Therefore, the final sample consisted of 11 participants (M_{age} = 22.45, *SD* = 1.29, range = 21-25; 8 female, 3 male). The experiment was approved by the Ethics Committee of the Faculty of Behavioural and Social Sciences of the University of Groningen.

Experimental Design

In all three experimental sessions, participants completed six blocks of a Posner cueing task. Each block was composed of 60 trials, 48 valid and 12 invalid trials, with a short break in between. Before experimental data were collected, participants completed two practice rounds of 20 trials each, to get used to the task, which were not included in the data analysis. These practice rounds were completed in each session. The visual stimuli were presented on a computer screen at a distance of 73 cm, measured from the eyes to the fixation point on the screen, which was at eye level. In order to maintain participants' head position, a head rest was used. To ensure comfort during completing the task, the height of the table could be adjusted, which did not require any further adaptation of the equipment.

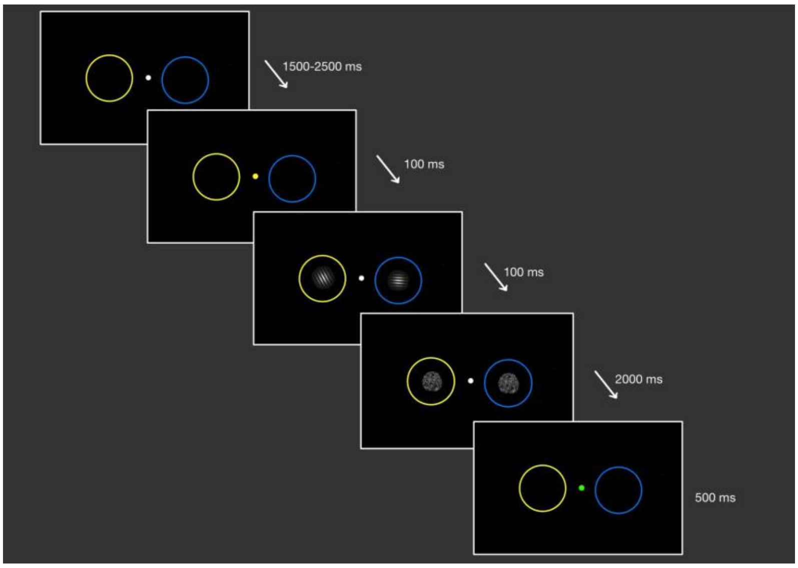
To begin with, participants were instructed to fixate on a white point in the middle of the screen (x = 0, y = 0) against a black background. Next to the fixation point, there was one hollow blue or yellow circle on each side (no fill, r = 96, penwidth = 4). The side at which the colours were shown was counter-balanced between participants. The fixation point in the middle changed colour to either blue or yellow for a period that was jittered between 1500 and 2500 ms, indicating the location of the target stimulus. The target stimulus was presented for 100 ms on either the cued or the opposite side, corresponding to valid or invalid trials, respectively. The target was a black and white Gabor patch that varied between a 1° and 10° tilt either to the left or the right. The other side displayed a neutral stimulus, a gradient tilting at 90°. After the stimulus presentation, a mask was shown of a scrambled grating for 100 ms. Participants were instructed to press either the left or right arrow key on the keyboard in front of them, indicating the direction of the gradient tilt, within a limited time window of 2000 ms after target onset. Afterwards, the fixation point in the middle turned green in cases of correct responses and red for incorrect responses (500 ms). If they failed to respond within the allotted time, the trial was counted as incorrect. One trial lasted a total of approximately 5 seconds.

To ensure that participants maintained their gaze on the fixation point, an eye tracking device was used, which was calibrated and validated before the trials. The validation error rate had to be below 1° before the trials could begin. After each trial, gaze correction was applied to further ensure the fixation on the central point. Consequently, participants could only start the next trial once their eyes were fixated in the middle. Eye tracking was also used during the task, but this data will not be analysed in this thesis.

At the end of each session, participants completed a short online questionnaire asking about the sensations they experienced during the task and the intensity of those sensations. After the third session, an additional question was included, asking participants to guess which condition they believed was the sham.

Figure 1

Posner Task - Example of a Valid Experimental Block



Note. Participants fixated on a white fixation point in the centre, which turned to yellow after 1500-2500 ms. Then, the target appeared within the yellow circle (100 ms), indicating a valid trial, and was immediately masked by a scrambled grating (100 ms). Participants had 2000 ms to press the correct key. After responding, they received feedback: the fixation point turned green to indicate a correct response.

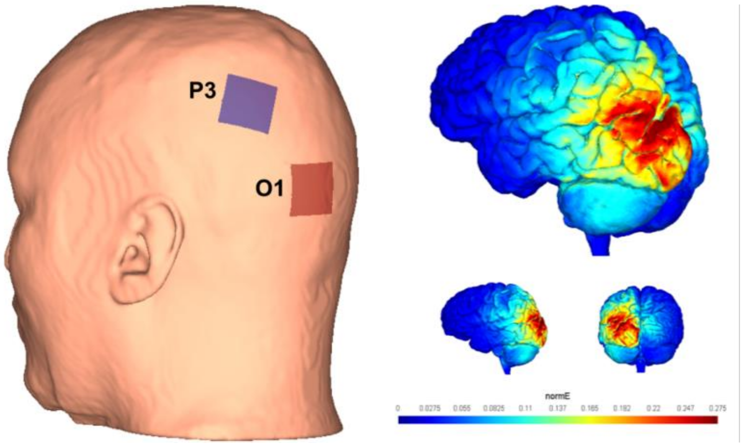
Electrical Stimulation

Participants received 10 Hz alpha tACS during the three experimental sessions over the occipito-parietal cortex. The order of stimulation conditions (left, right, sham) was randomized. During the sham stimulation electrodes were placed on the left or right hemisphere randomly. The stimulation lasted approximately 40 minutes, during the experimental trials in the left and right stimulation conditions. However, during the sham condition, participants received a short stimulation, which amped up and down in the duration of 60 seconds to make it long enough to still feel the stimulation, but short enough to have no effect. Two 3x3 cm conductive rubber electrodes were placed over the occipito-parietal cortex. The posterior electrodes were placed over the O1 and O2 regions, while the anterior electrodes were placed over the P3 and P4 regions for left and right hemispheric stimulation respectively. These areas were cleaned using Nuprep to ensure that impedance remained below 20 kOhm. Afterwards, the rubber electrodes were attached using Ten20 Conductive Paste. Figure 2 shows the placement of the electrodes and the expected electrical field they would stimulate.

Before each session, participants were gradually introduced to the stimulation, starting at 750 μA, then increasing to 1400 μA, and finally reaching 2000 μA, the experimental stimulation intensity. This was essential to make sure the participants were comfortable with the feeling of tACS. No stimulation was applied during the practice trials; it was only restarted during the 6x60 experimental trials.

Figure 2

Placement of the tACS Electrodes Over the Occipito-Parietal Cortex



Note. The two electrodes were placed over the O1 and P3 regions for left hemispheric stimulation. The expected electrical field generated by these electrodes is shown on the right. The more red the area, the higher the intensity of the induced electric field, measured in mV/mm. The maximum field strength reached was 0.275 mV/mm.

Statistical Analysis

For statistical analysis, JASP was used. Repeated Measures Analysis of Variance (RM-ANOVA) was performed using behavioural data, reaction time (RT) and accuracy, as dependent variables. The analysis included three independent variables: *tACS*, *Validity*, *Hemifield*. *tACS* refers to the stimulation conditions (left, right, sham), *Validity* to the validity of the cues (valid, invalid), and *Hemifield* to the left or right side of the visual field. Trials where participants failed to react on time were completely removed from the data set. Furthermore, outliers of RTs were removed, on the basis of being 2.5 SDs above the mean. Due to the small sample size, demographic data were not analysed.

Results

Behavioural data were analysed to examine accuracy and reaction time across stimulation conditions. A three-by-two-by-two RM-ANOVA was conducted with accuracy as dependent variable, and *tACS*, *Validity* and *Hemifield* as independent variables. *Validity* yielded a statistically significant main effect ($F(1,10) = 21.93$, $p < .001$). Therefore, there was a significant difference in the accuracy of participants during valid and invalid cue presentations. Analysis of marginal means indicated that participants were more accurate during valid trials (M = 91.0, SE = 1.5) compared to invalid trials (M = 86.1, SE = 1.5). Thus, when the cue appeared on the cued side, participants were more accurate in their responses compared to when it appeared on the opposite side, supporting the hypothesis.

Looking at the interaction effect of *tACS* and *Hemifield*, which was the main effect of interest, no statistically significant effect was found ($F(2,20) = .68$, $p = .518$). Therefore, contrary to our hypothesis, tACS did not differentially affect accuracy based on which hemifield the target appears on. No other statistically significant main effects (*Hemifield* ($F(1,10) = 4.12$, $p = .07$); *tACS* ($F(2,20) = .18$, $p = .84$)) or interaction effects (*tACS*Validity* ($F(2,20) = .2$, $p = .82$); *Validity*Hemifield* ($F(1,10) = 2.95$, $p = .12$)) were found for the dependent variable *accuracy*, failing to support the hypotheses. The results are shown in Figure 3 below.

Considering reaction times (expressed in milliseconds), *Validity* yielded a statistically significant main effect ($F(1,10) = 15.96$, $p = .003$). Therefore, participants' RTs were faster in valid trials compared to the invalid ones. Examining the marginal means, valid trials were faster ($M = 534.3$, $SE = 20.9$), while invalid trials were slower ($M = 689.4$, $SE = 50.5$), thus supporting the hypothesis.

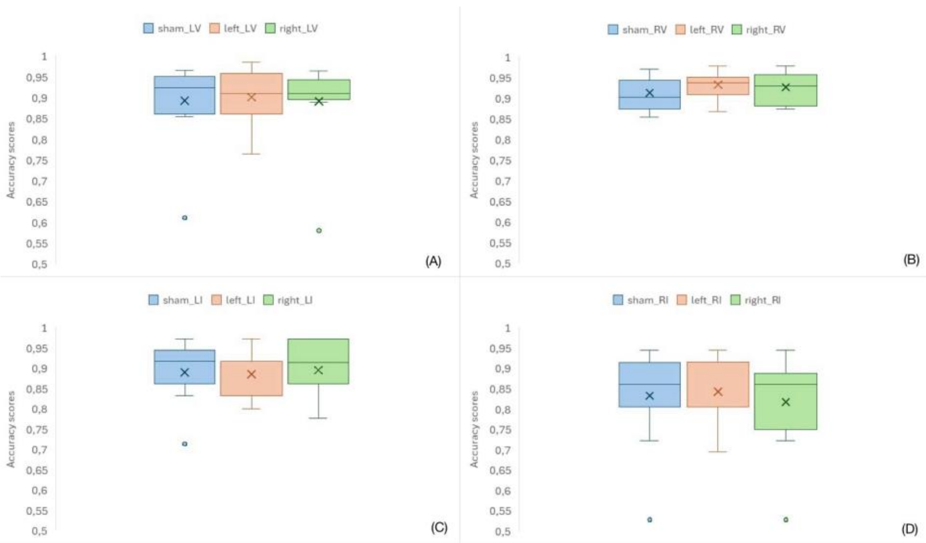
The independent variable *Hemifield* yielded a marginal, but non-statistically significant main effect ($F(1,10) = 4.88$, $p = .052$). This indicates a non-significant tendency toward faster reaction times in one hemifield over the other. However, as this is an interim analysis, these results may change and could potentially yield a significant main effect with a larger sample.

Nevertheless, an unexpected statistically significant interaction effect was found between *Validity* and *Hemifield* ($F(1,10) = 7.91$, $p = .018$). Analysis of the marginal means revealed that both the left ($M = 558.1$, $SE = 25.1$) and right ($M = 510.5$, $SE = 18.3$) hemifields in the valid condition resulted in faster RTs compared to the left (*M* = 674.04, *SE* = 49.5) and right (*M* = 704.7, *SE* = 52.7) hemifields in the invalid conditions. It is evident that the attentional cueing effect was stronger in the right hemifield, as the difference between valid and invalid trials was more pronounced compared to the left hemifield. This interaction effect was further examined using a Bonferroni corrected simple-effects test. The results showed that participants responded significantly faster in the right hemifield during valid trials ($t(10) = 3.3$, $p_{bonf} = .04$), whereas the difference between invalid trials in the left hemifield and invalid trials in the right hemifield was not significant ($t(10) = -2.12$, $p_{bonf} = .34$).

Considering the interaction between *tACS* and *Hemifield* for RTs, no statistically significant effect was found ($F(2,20) = .13$, $p = .88$). This indicates that contrary to our hypothesis, when tACS was applied and the cue appeared in either the left or right hemifield, it did not influence reaction times, resulting in a null effect. No other statistically significant main (*tACS* ($F(2,20) = .31$, $p = .74$)) or interaction effects (*tACS*Validity* ($F(2,20) = .4$, $p = .68$); *tACS*Hemifield* ($F(2,20) = .13$, $p = .88$)) were observed in relation to RTs. The values are presented in Figure 4.

Figure 3

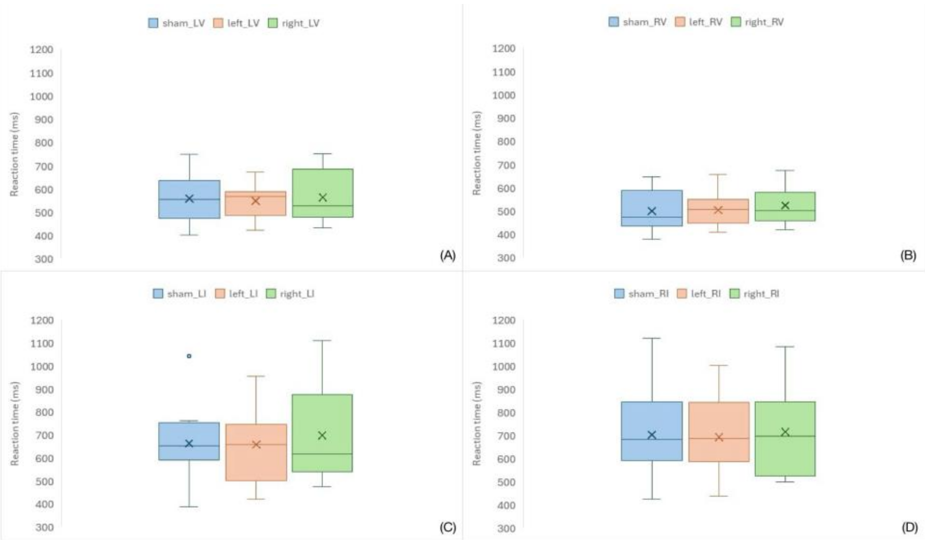
Mean Accuracy Scores Across Stimulation Conditions



Note. (A) Accuracy scores across all stimulation conditions for valid trials in the left hemifield (LV = left valid). (B) Accuracy scores across all stimulation conditions for valid trials in the right hemifield (RV = right valid). (C) Accuracy scores across all stimulation conditions for invalid trials in the left hemifield (LI = left invalid). (D) Accuracy scores across all stimulation conditions for invalid trials in the right hemifield (RI = right invalid).

Figure 4

Mean Reaction Times Across Stimulation Conditions



Note. (A) Reaction times across all stimulation conditions for valid trials in the left hemifield (LV = left valid). (B) Reaction times across all stimulation conditions for valid trials in the right hemifield (RV = right valid). (C) Reaction times across all stimulation conditions for invalid trials in the left hemifield (LI = left invalid). (D) Reaction times across all stimulation conditions for invalid trials in the right hemifield (RI = right invalid).

Discussion

This thesis aimed to present a conceptual replication study to examine whether applying alpha tACS over the left or right occipito-parietal cortex has an effect on visuospatial attention in the contralateral hemifield. As hypothesised an effect on the validity of cueing was found, meaning that participants responded more quickly and more accurately on validly cued trials compared to invalid ones. However, the hypotheses regarding the efficacy of tACS were not supported. No significant differences in reaction times or accuracy were observed between stimulation conditions. These null results suggest that, under the conditions of the current experiment, alpha tACS did not reliably modulate visuospatial attention.

Our replication of the validity effect aligns with findings from decades of previous studies, such as those by Posner (1980) and Van der Stigchel and Theeuwes (2007), who reported that participants perform worse during invalid trials compared to valid ones. One possible explanation is inattentional blindness, which refers to the failure to detect unexpected stimuli (Most et al., 2005). Consequently, individuals may be slower to respond when an irrelevant stimulus contains information that conflicts with the stimulus they are supposed to focus on (Pugnaghi et al., 2020). In the context of the current task, the invalid cues can be considered a type of irrelevant stimulus that interferes with processing at the target location. As participants mentally shifted their attention toward the cued side, they may have failed to respond correctly when the target appeared elsewhere, leading to decreased accuracy and delayed responses in invalid trials. This consistent pattern of delayed responses and reduced accuracy in invalid trials, even in the context of tACS, further supports the replicability of the Posner cueing effect.

The hypotheses concerning tACS were not supported by the results, failing to replicate previous findings. However, the present results align with the null findings reported by Coldea et al. (2021), who failed to find support for lateralized tACS inducing a shift in attention bias, away from the contralateral hemifield, and towards the ipsilateral hemifield. Similar to the current study, they placed electrodes over the P3 area and participants completed a conceptually similar visuospatial attention task. Additionally, Hopfinger et al. (2016) applied 10 Hz tACS over the right parietal lobe and reported no effect of alpha stimulation on endogenous attention. Further support is found in a study by Silas et al. (2023), who found no influence of tACS on tactile spatial attention; the observed reaction times and attention effects did not differ between stimulation and sham conditions.

These null results may suggest several possibilities. One possibility is that tACS at the alpha frequency may have limited efficacy in modulating visuospatial attention when using lower intensities. For example, Zhao et al. (2024) suggested that tACS at higher intensities, more specifically higher than 0.3 mV/mm, is more effective. During the current study, the maximum value reached could have only been 0.275 mV/mm, which could indicate the need for higher intensities and a more rational parameter selection during stimulation. Moreover, individual variability could play a significant role in the effectiveness of stimulation. Therefore, more personalized approaches, such as tailoring stimulation parameters to individual neural profiles, like intensity, may help to reduce variability, thereby increasing the likelihood of effective modulation across participants (Van Hoornweder et al., 2022).

It is also important to consider other frequency bands that play a significant role in attention. For instance, alongside alpha, gamma oscillations have been shown to reflect endogenous attention, as they are amplified during stimulus processing (van Ede et al., 2014). For example, in the previously mentioned study by Hopfinger et al. (2016), while alpha stimulation yielded no results, stimulation in the gamma band (40 Hz) resulted in an improved disengagement from invalidly cued targets in the endogenous attention task. This is particularly interesting given that the phase of alpha activity has been shown to couple with the amplitude of high-frequency gamma activity (30–200 Hz) (Van Diepen et al., 2019). Furthermore, alpha power has been shown to be inversely related to neural signals such as spiking activity and gamma-band oscillations, supporting the view of alpha oscillations as a suppressive mechanism (Foster & Awh, 2019).

These findings align with those of Kasten et al. (2020), who applied tACS over the occipital and posterior parietal cortices using both individualised alpha frequencies and a 47

Hz gamma frequency. During endogenous attention tasks, they observed a differential effect of gamma tACS on the spatial cueing effect in the left occipital cortex, while alpha tACS revealed an inhibitory effect, highlighting the distinct roles of frequency bands in attentional processes. Therefore, stimulating different bands or using individualised stimulation frequencies, may be a crucial factor to consider when aiming to establish a causal link between alpha oscillations and visuospatial attention.

Supporting this, Kemmerer et al. (2022b) applied tACS to the left posterior parietal cortex and observed a clear leftward attention bias during the endogenous task when stimulation was delivered at each participant's individual alpha frequency. A significant correlation was found between alpha lateralization and the attentional bias effect only under this condition, reinforcing that alpha oscillations play a frequency-specific role in visuospatial attention and that tACS tailored to individual neural dynamics has the potential to modulate this process.

In contrast, the present study applied a fixed stimulation frequency of 10 Hz across all participants. The lack of observed effects in our study may, therefore, be partially attributed to the absence of individualised stimulation. Given that individual alpha peak frequencies differ from person to person (Christoffersen & Schachtman, 2016), applying a non-matching frequency may have failed to align with the brain's natural oscillatory activity. This underscores the potential importance of accounting for individual neural dynamics when attempting to modulate cognitive processes like attention through tACS.

Another potential explanation for the null findings could lie in the phase of the stimulation. Busch and VanRullen (2010) provided electrophysiological evidence that sustained attention is modulated periodically. In their experiment, detection performance fluctuated over time in synchrony with the phase of spontaneous ~7 Hz oscillations occurring just prior to stimulus presentation. This suggests that attentional enhancement operates rhythmically, rather than continuously. Supporting the importance of phase, other studies have shown that the effectiveness of tACS depends on its phase alignment. For example, out-of-phase tACS has been found to disrupt top-down inhibitory control in a Stroop task, indicating that precise phase relationships may be crucial for effective neuromodulation (Kim et al., 2024; Seo et al., 2024). More specifically, phase-dependent tACS has been shown to improve long-range connectivity and enhance task-specific network activity and communication between distant networks (Wischnewski et al., 2023). The lack of phase alignment between tACS and alpha oscillations in the current study may have limited its effectiveness, potentially accounting for the absence of significant behavioural effects.

Additionally, a result not originally hypothesised was found regarding reaction times. When cues appeared in the right hemifield, participants showed greater variability in reaction times in comparison to the left hemifield. Additionally, reaction times in the left hemifield were generally slower relative to the right hemifield. While the direction of the effect differs, this aligns with the findings of Schuhmann et al. (2019) and Kemmerer et al. (2020a), who both applied tACS while measuring reaction times in various attention tasks. They reported faster responses to left-sided targets during endogenous tasks, which may suggest underlying asymmetries in attentional processing. While the current study found no direct link with tACS, the findings are broadly consistent with the idea that visuospatial attention may be biased toward the left visual field, and that alpha oscillations play a role in modulating such biases.

The current study faces some limitations. As this is an interim analysis with a limited sample size, the findings are preliminary and should be interpreted with caution, not considered conclusive. Prior to data collection a power analysis was performed, which revealed that a minimum of 30 participants are needed to ensure the validity of the results (the preregistration of the overall project can be found by clicking this LINK). Additionally, the sample consists mostly of women within a narrow age range, limiting the generalisability of the results. A more diverse sample would be necessary to explore potential sex differences and to draw more representative conclusions.

Factors such as time of day, genetic disposition contribute to the variability in brain stimulation effects. Furthermore, individual differences in head anatomy could result in variability in the distribution and intensity of the induced electric fields (Kasten et al., 2020). As discussed earlier, the use of individualised stimulation frequencies may be the gateway to finding the causal connection between alpha oscillations and visuospatial attention. Mismatches between an individual's dominant oscillatory frequency and the mixed frequency used for tACS have been repeatedly suggested as a source of inconsistent results (Kasten et al., 2020).

Furthermore, individual variability in tissue conductivity, being a biophysical property, can affect how stimulation is distributed across the brain. Since the place of the electrodes were measured manually and there were no fixed anatomical points, it may have resulted in suboptimal positioning. If electrodes were positioned too closely together, it could have led to a lower intensity of electric fields reaching the targeted brain areas (Wischnewski et al., 2023).

Conclusion

The current thesis aimed to present a conceptual replication study investigating whether applying alpha tACS over the occipito-parietal cortex affects visuospatial attention. The Posner attentional effect was successfully replicated, with valid targets resulting in faster and more accurate responses during an endogenous visuospatial attention task. Additionally, a somewhat unexpected result was found: reaction times were faster when attention was directed to the right hemifield. The absence of tACS effect seems to be in line with previous studies reporting no modulation of attention by 10 Hz stimulation. However, a larger sample size is required to solidify this null finding.

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