The Influence of Frontal Theta-tACS on Verbal versus Visuospatial Working Memory Performance

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Abstract

Working memory (WM) is a system that is responsible for storing and manipulating information necessary for cognitive tasks. It can be broadly divided into a verbal and visuospatial component. Although much research has been conducted it still remains unclear whether brain stimulation affects both verbal and visuospatial WM similarly. Therefore, this study aims to investigate what the effects are on verbal and visuospatial WM performance using fronto theta transcranial alternating current stimulation (tACS). A single blind, within-subject, placebo-controlled study was conducted to investigate the effects. The verbal WM was assessed using a letter-based N-back task whereas the visuospatial WM was assessed with a Change Detection Task (CDT). A repeated measures design was used that consisted out of two sessions (active/sham condition). Healthy adults (N=20) were recruited using a convenience sample and later randomized and counterbalanced. The results show that fronto theta-tACS did not affect the verbal WM. In contrast, the visuospatial did show an effect of fronto theta-tACS. The visuospatial WM task showed a higher accuracy when active stimulation was applied. The effect of the stimulation emerged more clearly as task difficulty increased. This indicates that the effect of tACS is influenced by task difficulty. However, the results should be interpreted with caution as possible ceiling effects may have occurred for the verbal WM task, leading to no significant results. In addition, the small sample size may have contributed to less clear results. Nevertheless, the present study contributes to a better understanding of the mechanisms of tACS in modulating specific types of WM.

Keywords: tACS, working memory, Change Detection Task, N-back, theta, frontal brain stimulation

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Working memory (WM) is a cognitive system that temporarily stores and manipulates information necessary for complex cognitive tasks. Baddeley and Hitch (1974) divide this system into three main domains: the phonological loop, the visuospatial working memory, and central executives. Later, they added a new component: the episodic buffer, which links the verbal and visuospatial working memory to long-term memory (Baddeley, 2000). Since working memory requires executive functions as well as content-specific processing (e.g. verbal information), it engages a widespread cortical network. The frontal cortex is activated with the executive functions whereas the posterior areas (e.g. parietal cortex) are activated for specific content processing (Miller et al., 2018).

Studies have shown that the prefrontal cortex (PFC) is seen as the control mechanism when it comes to working memory. It is suggested that the PFC is responsible for distinguishing task relevance information and directing focus accordingly. The PFC therefore is mainly focused on the control mechanisms of working memory and not storage of information itself (Lara & Wallis, 2015). This is also supported by a study done with monkeys (Lara & Wallis, 2014). In this study they focused on monkeys with lesions in the PFC. The results showed that these monkeys were unable to rapidly shift attention. In addition, the majority of neurons in the PFC were also unable to maintain the content of the presented stimuli. Creating evidence that the PFC is responsible for executive functions. In this case, the PFC uses a top-down approach. Meaning that information comes in and is directed towards the corresponding responsible area. Supporting the idea that the PFC is not the only one responsible for working memory processes.

The PFC is also closely communicating with posterior areas of the brain, called the sensory cortices (Lara & Wallis, 2015). The sensory cortices include the auditory, visual and gustatory cortices. Lara and Wallis (2015) state that all the factual representations of information are stored in the corresponding areas of these cortices. This is affirmed by several studies done with functional imaging. One of them showed increased activity in areas associated with orientation when participants were asked to remember specific directions of grating (Emrich et al., 2013). In contrast to the PFC, WM here utilizes a bottom-up approach. Incoming information of the PFC is linked to the existing representations (Miller et al, 2015). Nevertheless, when actively modulating incoming information, a spike in neural oscillations is seen within all of the relevant regions (Buzsáki & Wang, 2012; Miller et al., 2018).

Neuronal oscillations are rhythmic and repetitive fluctuations within the central nervous system that represent the neural activity. These oscillations are the result of interactions between neurons (Cohen, 2017). Although it is challenging to precisely define the frequency range in which neuronal oscillations operate, the most relevant range for now covers frequencies between 1 Hz and 200 Hz. Over the years, various patterns of these oscillations were identified within this broad range, showing that frequencies are associated with distinct cognitive states (Buzsáki & Draguhn, 2004). For example, the lowest frequency band delta (0.5 - 4 Hz) is often associated with deep sleep and loss of consciousness, whereas the highest band gamma (>30 Hz) is often associated with problem solving and working memory. Nevertheless, all frequencies are found in every different cognitive state and interact with each other (Buzsáki & Wang, 2012; Miller et al., 2018).

The interaction between different frequency bands is also observed in the WM. WM tasks induce a spike in neuronal activity. Multiple studies using EEG and MEG have reported a significant spike in theta oscillations in the PFC during WM task execution (Pahor & Jausovec, 2018; Lara & Wallis, 2015; Roux & Uhlhaas, 2014; Jausovec et al., 2014). This reflects enhanced executive function and temporal organisation of stimuli. According to Roux and Uhlhaas (2014), theta oscillations provide the optimal structure to eventually organize content-specific stimuli in the sensory cortices. Information processed in these cortices is subsequently maintained with the aid of gamma waves (Pahor & Jausovec, 2018). Gamma here reflects a general mechanism for the representations of the individual WM items (Roux & Uhlhaas, 2014). Thus, theta and gamma oscillations interact closely to support WM processes.

Furthermore, several studies have demonstrated a strong positive correlation between the synchronization of theta waves and an increase in WM performance (Polania et al., 2012; Liebe et al., 2012; Violante et al., 2017). These effects have been observed by using brain stimulation techniques to enhance synchronization in theta oscillations. The synchronization is found to enhance communication between different brain areas. Notably, one study reported that desynchronizing theta oscillations led to impaired WM performance in contrast to no stimulation (Alekseichuk et al., 2016). Providing more evidence for previous findings (Polania et al., 2012; Liebe et al., 2012; Violante et al., 2017).

One non-invasive brain stimulation technique that allows synchronization between neuron oscillations is called *transcranial alternating current stimulation* (tACS). This technique has shown an increase in interest over the last few years given its flexibility and non-invasive nature. The tACS delivers a weak oscillating electric stimulation through the scalp (Agboada et al., 2025). The weak stimulation of tACS causes a 'nudge' in the resting membrane potentials of neurons. Thereby increasing the likelihood that the neuronal firing will align with the same pattern as the oscillations presented by the tACS. This results in synchronization in the firing of neurons in the stimulated brain area (Wischnewski et al., 2023).

The enhancement of working memory seems to be the most effective when tACS is applied to the prefrontal or parietal cortex. As these are key nods of the frontoparietal network that underlies WM functioning (Al Qasem et al., 2022; Palva et al., 2010). Nevertheless, stimulation effects appear to depend on both task type and stimulation site. For example, there is evidence that applying tACS to the inferior fronto-parietal network shows an increase in performance on visuospatial tasks (Ociepka et al., 2025). Whereas, Biel and colleagues (2022) show that performance on verbal tasks enhances when tACS is applied to the more frontal areas of the fronto-parietal network.

As theta oscillations play a central role in processing incoming information in WM, theta-tACS is particularly relevant when examining WM accuracy. Wischnewski and colleagues (2024) compared 28 tACS studies to identify causal functional maps of neural oscillations. They found that theta stimulation increased WM accuracy when applied to the anterior prefrontal cortex and medial temporal cortex. In contrast, they found that gamma stimulation is most effective when stimulating the occipital parietal areas and even impaired WM accuracy when administered to frontal areas. Aligning with findings discussed earlier (Ociepka et al., 2025; Biel et al., 2022).

Together, these findings illustrate that WM relies on the coordinated activity of multiple components as explained by Baddeley and Hitch (1979). Theta oscillations appear to play a central role in coordinating these components by temporally organizing incoming information and directing attention via the PFC. Evidence shows that enhancing theta synchronization with tACS improves the efficiency of these processes by strengthening executive control in PFC and facilitating the transfer of information to modality-specific regions in the brain (Ociepka et al., 2025; Wischnewski et al., 2024; Biel et al., 2022). However, because the phonological loop and visuospatial WM depend on distinct neural systems, it remains unclear whether frontal theta-tACS benefits verbal and visuospatial processing equally. This study therefore aims to investigate the effects of fronto theta-tACS on performance in verbal tasks versus visuospatial tasks in healthy adults. The hypothesis is that frontal theta-tACS will improve verbal WM more than visuospatial WM as this is processed in prefrontal regions (e.g. Broca's area), located directly beneath the stimulation site (Rodd et al., 2015). In contrast, visuospatial tasks depend on parietal regions located further from the stimulation site (Zhang & Weng, 2018). Therefore, frontal theta-tACS is expected to enhance verbal task performance more than visuospatial tasks.

Method

Participants

A total of 20 healthy adults (> 18 years) participated in this study. The first two participants were excluded as different task timing was used. Another two participants were excluded due to failure of the computer. Resulting in a total of 16 participants. All participants were recruited through convenience sampling. Exclusion criteria comprise the presence of metal implants in or near the head, a history of epilepsy, dermatological conditions near the site of stimulation, active psychiatric disorders, pregnancy, and color blindness. The Ethics Committee of the Faculty Behavioural and Social Sciences of the University of Groningen provided ethical approval for this study. Upon starting the first session and finishing the second session, written informed consent was obtained. The data was collected between November 10 and December 18 2025.

This study applies to a single-blind, within-subject, placebo-controlled design. Each participant completed two experimental sessions, at least one week apart to limit carry-over effects. In one of these sessions the participants received active theta-frequency tACS, while in the other they received a sham condition. The session conditions were randomized and counterbalanced. Therefore, 50% of the participants began in the sham condition and 50% in the active condition. The participants were blind to the condition which they received. Both sessions took place in the morning between 08:00 and 11:00 and lasted approximately 75 minutes.

Procedure

The sessions started with several questionnaires for the participant to complete and placement of a heart rate monitor. Details on these measurements are reported elsewhere. After the questionnaires, the stimulation electrodes were placed on the scalp of the participants. Each session started with a practice block that introduced the two digital cognitive tasks used in this study: a visuospatial and verbal working memory task. No stimulation was applied during the practice block. During both practice and the main condition the order of tasks was kept the same, with the visuospatial task preceding the verbal task, to ensure the same setting for all participants. The practice trial was implemented to limit learning effects during the main block. Upon starting this task, a verbal and written instruction was given to ensure the task was understood correctly.

Tasks

Visuospatial working memory was assessed using a change-detection task (CDT) (Figure 1). In this task the difficulty was determined by the number of blocks presented to the participant and ranged between three different levels: 'moderate' (four blocks), 'high' (six blocks), and 'very high' (eight blocks). The stimuli consisted of an array of different color blocks. The colors could be one out of 21 implemented colors (e.g. red, cyan, olive). These were presented for 400 ms, followed by a color-change mask for 5 ms. After a delay of 1000 ms, participants were presented either the same or a different array of colored blocks and were prompted to indicate whether or not the second array matched the first. They had 2500 ms to respond. Immediate feedback was provided after each response via a green (correct) or red (incorrect) indicator for 300 ms. When finishing all three difficulty levels, the task was repeated once more. The total duration of this task was 180 trials, evenly divided over all difficulty levels. During the practice trial, only levels 'moderate' and 'high' were reviewed. Adding up to a total of 30 trials, resulting in 15 trials per level.

The verbal task was assessed using an N-back task (Figure 2). Two difficulty levels were included: a 2-back and a 3-back condition. The stimuli could be one of the first eight letters of the alphabet. They were presented sequentially for 750 ms each with 1200 ms between the letters during which a fixation point was shown. Responses were recorded during the stimulus presentation, resulting in a response window of 750 ms. In this window the letter became green (correct) or red (incorrect) according to the response. If the letter did match N letters back, the participant was prompted to press the spacebar. Otherwise, they were instructed to refrain from responding. The task consisted of 120 trials, evenly divided over difficulty levels. During the practice trial, only 40 trials were reviewed, resulting in 20 trials per level.

Opensesame v4.1 was used to run the CDT and N-back task.

Figure 1

Graphic description of CDT

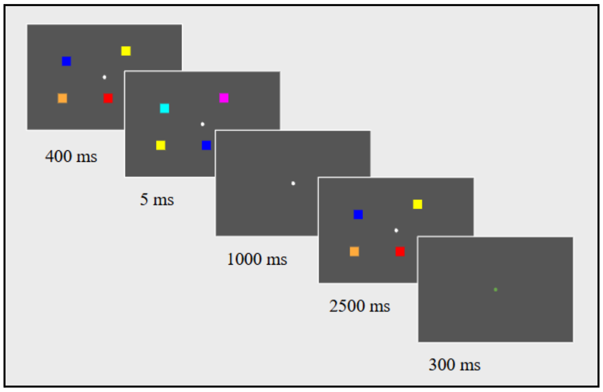
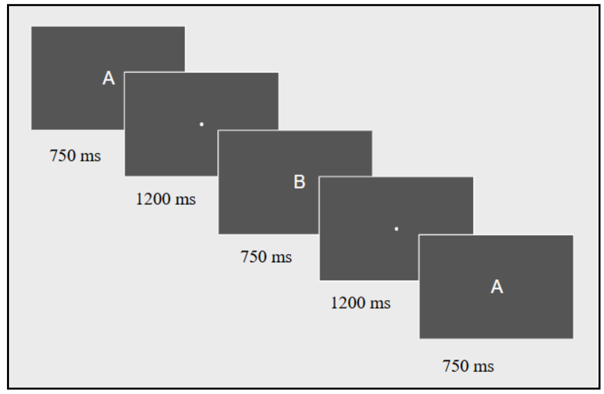


Figure 2

Graphic description of N-back



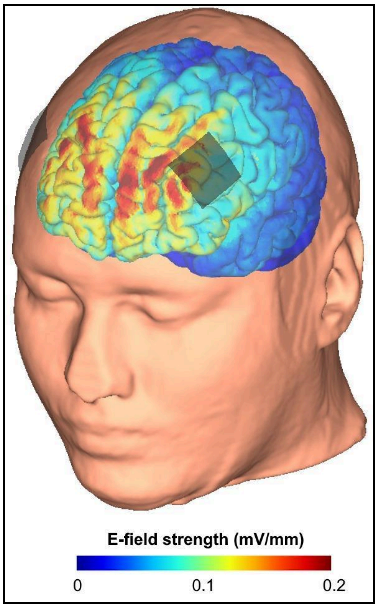
Stimulation

After the practice trial, participants were given a brief familiarization trial for the stimulation during which the intensity gradually increased to a maximum of approximately 1.5 mA. No test was conducted during this period. The familiarization trial was done in both conditions (sham/active). Upon starting this trial, participants were informed about potential adverse effects (e.g. burning sensation, light flickering). When these effects were experienced, pressure was applied to the electrodes by the researcher.

The tACS stimulation was applied using *NeuroConn DC-stimulator plus.* During the active condition, tACS was applied at 4 Hz with an intensity of 1.5 mA (peak-to-peak). Rubber electrodes were used together with conductive paste (*Ten20 Conductive Paste*). Upon applying the electrodes, the sites of stimulation were thoroughly cleaned with *Nuprep skin prep gel*. The sites of stimulation matched F3 and F4 using the 10-20 EEG system (Jasper, 1958) (see Figure 3). The impedance was kept below 20 kΩ but it was aimed to be as low as possible. At the start of stimulation, the current was ramped up over 30 seconds. Stimulation had a maximum duration of 30 minutes. During the sham stimulation, the current intensity was gradually increased to 1.5 mA and subsequently ramped down until no stimulation was delivered. This ramping procedure lasted 30 seconds.

Figure 3

Induced electric fields using a stimulation site F3 and F4, as calculated with SimNIBS 3.2. The simulation suggests a primary target of lateral and medial PFC.



Analysis

The data gained from this study was analyzed to answer the research question "*What are the effects of fronto theta-tACS on performance in verbal tasks versus visuospatial tasks in healthy adults?*". Using JASP (version 0.18), two repeated measures analyses of variances (RM-ANOVA) were generated. For the N-back task a 2x2 RM-ANOVA was applied. The two factors in this analysis were *Difficulty* (2-back or 3-back) and *Stimulation* (active or sham). For the CDT, a 3x2 RM-ANOVA was applied. Here the factors were *Difficulty* (moderate, high or very high) and *Stimulation* (active or sham). The main effects of *Stimulation* and *Difficulty* were investigated in each task, along with the interaction effect between the factors. Lastly, the descriptives of the overall means of both tasks were generated using JASP. The overall means combine all difficulty levels but differentiate between stimulation conditions per task. The dependent variable in this study was the proportion of correct responses of each participant. Assumptions were checked before the analysis.

Results

The assumptions of independence, normality, and sphericity were examined prior to the analyses. Independence of observations was assumed, as participants were tested individually. Normality was assessed by inspecting Q–Q plots of the residuals. This revealed no extreme deviations from normality. The assumption of sphericity was automatically met for all factors with two levels. However, for the '*Difficulty*' factor of the CDT, Mauchly's test indicated a violation of sphericity ($W = 0.591$, $p = .025$). Consequently, Greenhouse–Geisser correction was applied to the degrees of freedom ($\varepsilon = .71$) to limit the possibility of false positives. Lastly, boxplots were examined to identify potential outliers. Three outliers were detected in the N-back task and consequently deleted ($n = 13$) to limit distorted results. For the CDT no outliers were detected ($n = 16$).

For the N-back task A 2×2 RM-ANOVA showed a significant main effect of '*Difficulty*' , $F(1, 12) = 49.137$, $p < .001$, partial $\eta^2 = .804$, indicating lower accuracy in the 3-back condition compared to the 2-back condition. The main effect of '*Stimulation*' was not significant, $F(1, 12) = 0.123$, $p = .732$, partial $\eta^2 = .010$. Additionally, the '*Difficulty*' x '*Stimulation*' interaction was not significant, $F(1, 12) = 0.050$, $p = .827$, partial $\eta^2 = .004$.

A 3×2 RM-ANOVA was conducted on the proportion of correct responses in the CDT. A significant main effect of '*Difficulty*' was observed using the Greenhouse–Geisser correction, $F(1.42, 21.296) = 31.765$, $p < .001$, partial $\eta^2 = .679$. In addition, a significant main effect of '*Stimulation*' was found, $F(1, 15) = 15.704$, $p = .001$, partial $\eta^2 = .511$. Furthermore, a significant '*Difficulty*' x '*Stimulation*' interaction was observed, $F(1.715, 25.718) = 6.425$, $p = .007$, partial $\eta^2 = .300$.

Given the significant interaction effect between '*Difficulty*' x '*Stimulation*' in the CDT, a post hoc paired T-test was conducted for each difficulty level. The Bonferroni correction ($\alpha = .017$) was applied to account for multiple comparisons. The results indicated no significant difference between the active or sham condition for the level 'moderate', $t(15) = -0.756$, $p = 0.461$, $d = -.189$. For the level 'high' a significant difference was found, $t(15) = 4.568$, $p < .001$, $d = 1.142$. Lastly, the level 'very high' did not reach statistical significance, $t(15) = 2.421$, $p = 0.029$, $d = 0.605$. That tACS makes an improvement in WM accuracy is supported by the descriptive statistics (Table 1). The overall mean of the CDT makes an improvement under active tACS stimulation with a mean difference of 0.042.

Table 1

Descriptive statistics of N-back and CDT tasks. Mean and standard deviation (SD) measured in proportion to correct responses.

Task and difficulty	Level	Mean	SD
N-back (overall mean)	Sham	0.880	0.055
	Active	0.877	0.068
N-back (2-back)	Sham	0.933	0.053
	Active	0.927	0.070
N-back (3-back)	Sham	0.826	0.071
	Active	0.826	0.077
CDT (overall mean)	Sham	0.650	0.049
	Active	0.692	0.061
CDT (moderate)	Sham	0.734	0.078
	Active	0.718	0.092
CDT (High)	Sham	0.641	0.076
	Active	0.734	0.078
CDT (Very high)	Sham	0.576	0.063
	Active	0.624	0.063

Discussion

WM uses a complex network within the brain which includes the prefrontal cortex (Lara & Wallis, 2015). Theta oscillations have been identified as key mechanism within the WM and prefrontal cortex (Pahor & Jausovec, 2018; Lara & Wallis, 2015; Roux & Uhlhaas, 2014; Jausovec et al., 2014; Polania et al., 2012; Liebe et al., 2012; Violante et al., 2017). This raises the question of whether frontal theta stimulation could alter WM performance. Specifically, the effects of neuronal synchronization with aid of tACS. The aim of this study was to investigate the effect of fronto theta-tACS on performance in verbal tasks versus visuospatial tasks in healthy adults. The hypothesis states that the performance of the verbal task would be affected more than the visuospatial task as the relevant areas lie directly underneath the stimulation site (Rodd et al., 2015; Zhang & Weng, 2018). \

The results showed that fronto theta-tACS stimulation did not affect the verbal WM performance. However, difficulty does influence the verbal WM performance, leading to lower performance as difficulty rises. This is also seen for the visuospatial WM. Higher difficulty levels resulted in a lower performance. However, the results also show that performance of visuospatial WM depended on the stimulation. Meaning that performance increased when active fronto theta-tACS was applied in comparison to the placebo condition.

The results of the N-back are in line with the findings of Pahor and Jausovec (2018). They demonstrated that an N-back task using verbal stimuli did not improve under active tACS. Despite this, they saw an emerging trend in better performance as difficulty increased. This suggestion is found by Biel and colleagues (2022). Their results indicate that higher task demands (e.g., a 3-back compared to a 2-back) may be more sensitive to tACS effects. In the current study, overall verbal WM performance was relatively high. Indicating a potential ceiling effect that may have limited the sensitivity of the task to detect stimulation-related improvements.

For the visuospatial WM, the results only align partially with the findings of previous research. The significant findings of the interaction effect between the difficulty levels and conditions directly contradicts the findings of Pahor and Jausovec (2018). In their research they found that there is no effect of theta-tACS on visuospatial WM performance, even though tACS did alter the brain in a resting state. However, they do suggest increasing the workload of the task would benefit the effects of tACS. This suggestion is found by Bender and colleagues (2019).

They found a significant effect of theta-tACS on visuospatial WM but only when the task was high memory load (>6 blocks). Indicating an interaction effect between difficulty and stimulation. This current study shows that fronto theta-tACS effects on visuospatial WM performance depends on task difficulty. Especially on more difficult levels the effects of tACS are seen more evident. Whereas smaller differences are observed less clearly among the lower difficulty levels, aligning with Bender and colleagues (2019). Interestingly, fronto theta-tACS seems to be most effective on the *'high'* level (8 blocks). Implying that the most effective difficulty level lies between six to eight blocks for the CDT. Nevertheless, greater variability was observed across difficulty levels when compared to the verbal WM task. This may contribute to a more clear emergence of significant effects for visuospatial WM.

The findings align with models proposing that fronto theta waves serve as a robust frame for gamma waves when looking at WM. This would lead to improved communication between brain structures (e.g. the PFC and sensory cortices) (Cooper et al., 2015; Biel et al., 2022; Jausovec & Pahor, 2014; Bender et al., 2019). Within these models theta stimulation is found to be the most beneficial when applied to the frontal cortex (Pahor & Jausovec, 2018). Aligning with previous research that found that WM triggers a spike in theta oscillations in the PFC as this reflects enhanced executive function (Lara & Wallis, 2015; Roux & Uhlhaas, 2014; Jausovec et al., 2014). This model is further supported by research of Wischnewski and colleagues (2024). Additionally, they found that when stimulating the parietal cortex, gamma is found to be the most effective. Indicating that stimulation effectiveness depends on stimulation location and frequency.

These models provide a plausible explanation for the findings in this current study. Previous research indicates that the PFC functions as a top-down control mechanism. This means that the PFC plays a central role in attention regulation and information filtering (Lara & Wallis, 2015; Wischnewski et al., 2024). The visuospatial task applied in this current study strongly relies on these executive functions. This may have elicited a more pronounced increase in theta activity compared to other tasks such as the N-back. This enhanced theta activity may have led to more effective neuromodulation. Thereby contributing to the observed performance effects.

An alternative explanation for the results can be drawn from the meta-analysis of Wischnewski and colleagues (2024). They propose that the dorsolateral prefrontal cortex (DLPFC) serves as an important linkage for verbal WM processing. However, neuromodulation targeting this area caused no significant effects. This lack of effect may be explained by the DLPFC's lesser dependence on specific oscillatory activity. The DLPFC could instead rely on alternative neural mechanisms. This may reduce the impact of tACS and therefore may lead to the results in this study.

Lastly, the findings of this study could be explained by the task difficulty differences. Multiple studies have demonstrated that the effects of tACS become more clear as task difficulty increases (Bender et al., 2019; Pahor & Jausovec, 2018; Biel et al., 2022). The results of this study show that the task for visuospatial WM showed a lower performance in contrast to the verbal WM task. This increased difficulty may have enhanced the sensitivity to tACS-induced modulation. Thereby contributing, together with the possible observed ceiling effects, to the more pronounced effects observed for visuospatial WM.

This current study has several notable strengths. A within-subject design with counterbalanced conditions was employed. Reducing order effects and enhancing internal validity. Additionally, sessions were separated by at least one week to minimize learning effects. Within each session, however, the order of tasks was kept constant to ensure a standardized testing environment across participants. Thereby supporting transparency and reproducibility.

Despite these strengths, the study also has limitations which should be considered when interpreting the results. First, the study is based on a relatively small sample size (N = 16). This limits statistical power and generalizability. Second, participants were recruited using a convenience sampling method. This increases the likelihood of selection bias, leading to distorted observations. Furthermore, the relatively high dropout rate (20%) may have further affected the reliability of the findings. In addition, ceiling effects seem to occur for the N-back. This may have led to unreliable results. Lastly, several individual variables were not taken into account in this study. Examples are baseline WM performance and tACS responsiveness.

Therefore, future research should focus on investigating the effects of individual variables. Along with implementing a more difficult verbal task to ensure reliable results. Furthermore, future research should focus on a larger, more diverse sample to ensure statistical power and generalizability. For the N-back specifically a more challenging task should be employed to prevent the occurrence of ceiling effects to fully capture the effects of tACS. Lastly, the interaction between difficulty and stimulation could also be investigated deeper.

Conclusion

The current study was designed to answer the research question "*What are the effects of fronto theta-tACS on performance in verbal tasks versus visuospatial tasks in healthy adults"*. The results indicate that theta-tACS appears to enhance visuospatial WM under conditions of high task load. Verbal WM however does not seem to improve under active tACS. Based on this study alone it could be concluded that visuospatial WM is affected more than verbal WM. An interaction between difficulty and stimulation suggests that WM performance increases as the WM load increases. However, the results of this study ought to be interpreted with care as the differences are subtle. Nonetheless, the results from this study are a valuable contribution for understanding the effects of fronto theta-tACS.

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Declaration of AI use

I acknowledge the use of NotebookLM (2025) to gain a better understanding of the materials. The prompt I used stated the following: “What are the main findings of this research?”.
I used the output to get a better understanding of specific studies and used it to plan out my thesis.
No large language model has been used to generate this thesis.