Effects of tACS Stimulation Timing on Working Memory Modulation

Authors: Guo Ruiqiao, Li Wenrui, Guo Xue, Zhao Na, Lei Ming, Liu Qiang, Liu Qiang

Date: 2025-12-11T00:00:00+00:00

Abstract

Although transcranial Alternating Current Stimulation (tACS) can enhance working memory (WM) performance by modulating cognitive resources, its effects have been inconsistent across existing studies. The present study reveals that the timing of tACS application relative to the task is a critical moderating variable determining the modulatory effects on WM. Through two rigorously designed experiments, we demonstrate that the modulatory effects of tACS on WM are influenced by the temporal relationship between stimulation and task: In Experiment 1, compared to sham stimulation, theta-band tACS (4 Hz, right parietal lobe) applied before practice significantly improved memory quantity while maintaining precision unchanged; whereas when stimulation was applied after practice, individuals had already formed a quantity-precision trade-off strategy for the task, which persisted under the influence of psychological inertia; that is, compared to sham stimulation, tACS selectively enhanced memory precision without altering quantity. Experiment 2 further revealed that the influence of stimulation timing on trade-off strategies does not transfer to new tasks; that is, strategies formed by subjects in the first task are disrupted in a new task: when faced with a new context, individuals develop new strategies based on task characteristics and their total available resources, demonstrating flexible reallocation of cognitive resources. Therefore, we conclude that the modulatory effects of tACS on WM depend on the timing of stimulation application: if applied before practice, it primarily affects memory quantity; if applied after practice, it primarily affects memory precision; however, the established modulatory effects do not transfer to new tasks.

Full Text

The Impact of tACS Stimulation Timing on the Modulation of Working Memory

Ruiqiao Guo[1] , Wenrui Li[2] , Xue Guo[3], Na Zhao , Ming Lei , Qiang Liu[1]

[1]Institute of Brain and Psychological Sciences, Sichuan Normal University, Chengdu 610066, China
[2]Psychology and Neuroscience of Cognition Research Unit, University of Liège, 4000 Liège, Belgium
[3]Non-Invasive Brain Stimulation Lab, Department of Neurology, University Medical Center Göttingen, Göttingen 37075, Germany
Brain and Cognitive Neuroscience Research Center, Liaoning Normal University, Dalian 116029, China
Psychological Research and Counseling Center, Southwest Jiaotong University, Chengdu 611756, China

These authors contributed equally to this work.

Abstract

Although transcranial alternating current stimulation (tACS) can enhance working memory (WM) performance by modulating cognitive resources, its effects have been inconsistent across studies. The present research identifies the timing of tACS application relative to task performance as a critical moderating factor. Through two rigorously designed experiments, we demonstrate that tACS effects on WM are temporally dependent. In Experiment 1, theta-frequency tACS (4 Hz) applied to the right parietal cortex before practice significantly improved memory quantity while preserving precision, compared to sham stimulation. When applied after practice, however, individuals had already formed a quantity-precision trade-off strategy that persisted due to psychological inertia—resulting in selective enhancement of memory precision without changes to quantity. Experiment 2 further revealed that this timing-dependent trade-off effect does not transfer to new tasks. When confronted with a novel task, participants broke their established strategy and formed a new one based on task demands and available resources, demonstrating flexible cognitive resource reallocation. We conclude that tACS effects on WM depend critically on stimulation timing: pre-task stimulation primarily affects memory quantity, whereas post-task stimulation mainly influences memory precision, with established effects failing to transfer to new tasks.

Keywords: tACS, working memory, accuracy-quantity trade-off, 4 Hz theta, psychological inertia

Introduction

Visual working memory (VWM) constitutes a core component of cognitive function, responsible for the temporary maintenance, manipulation, and storage of visual information. Research indicates that individuals with high VWM capacity outperform those with low capacity in problem-solving [?, ?], language comprehension [?, ?], and inhibiting irrelevant information [?, ?]. However, substantial individual differences exist in VWM capacity, and low capacity may constrain cognitive performance. Consequently, researchers have sought to identify effective non-invasive methods for enhancing VWM capacity to improve cognitive function.

In recent years, theta-frequency tACS has been shown to significantly improve WM performance by modulating neural oscillation synchrony in parietal regions [?, ?], with important implications for populations experiencing WM decline, such as older adults [?, ?]. The underlying mechanism involves theta-gamma cross-frequency coupling [?, ?, ?], wherein one gamma cycle corresponds to one memory item, with multiple gamma sub-cycles nested within a theta cycle. As memory load increases, theta frequency decreases [?, ?]. tACS delivers weak electrical currents at specific frequencies to synchronize brain oscillations, thereby affecting cognitive performance [?, ?, ?, ?]. Thus, low-frequency tACS (e.g., 4 Hz) can increase WM capacity by reducing individual theta frequency and lengthening the theta cycle to accommodate more gamma cycles. Notably, theta-gamma coupling primarily participates in the encoding phase of WM, whereas information maintenance relies on alpha (8–12 Hz) and beta (13–30 Hz) oscillations. Alpha oscillations protect WM representations by inhibiting irrelevant brain regions [?, ?], while beta activity updates and maintains memory contents [?, ?]. This functional dissociation suggests that theta-tACS effects may be phase-specific—enhancing information input efficiency during the encoding phase through theta-gamma coupling modulation, while exerting limited influence on the maintenance phase. The present study therefore focuses on theta-tACS effects on WM capacity, specifically examining its phase-specific role during encoding.

Despite promising evidence, tACS effects on WM remain inconsistent across studies. For instance, Zhang et al. (2022) found that theta-frequency tACS effectively enhanced visuospatial WM performance, whereas Kleinert & Müller (2017) observed no such benefit. These contradictions suggest that tACS efficacy may be influenced by multiple factors. A meta-analysis by Nissim et al. (2023) identified task difficulty [?, ?] and phase [?, ?] as significant moderators. Additional variables have also emerged: under high load, 4 Hz tACS significantly improved WM capacity compared to sham and 7 Hz stimulation [?, ?], indicating frequency-dependent effects. Target location represents another critical factor—4.5 Hz tACS applied to the right frontoparietal region selectively improved object WM, whereas bilateral prefrontal tACS showed no significant effects [?, ?], highlighting the parietal cortex's importance in WM [?, ?].

Crucially, stimulation timing may represent an important yet understudied factor. Studies applying stimulation before tasks consistently report significant WM enhancement from in-phase stimulation [?, ?, ?]. For example, Jaušovec et al. (2014) demonstrated that 15 minutes of pre-task parietal tACS significantly improved WM performance. Conversely, post-task stimulation studies show different patterns, with no significant effects on WM performance when stimulation follows task initiation [?, ?].

We propose that these discrepancies may reflect psychological inertia—the tendency for automatic behavior patterns to persist in repeated contexts [?, ?]. While psychological inertia maintains behavioral consistency and facilitates prediction [?, ?], it can also cause individuals to overlook optimal choices when in conflict with rational decision-making, increasing decision errors [?, ?, ?]. This aligns with Baddeley's multi-component model: the central executive system is highly involved in resource allocation and strategy selection during early task phases but becomes less engaged as tasks automatize [?, ?, ?]. Skilled tasks can be processed automatically through slave systems (e.g., phonological loop, visuospatial sketchpad), reducing central executive demands [?, ?, ?]. The neural basis of this automation may involve reduced frontoparietal activation. WM training studies show that initial learning requires high frontoparietal activation for conscious control, which decreases as tasks automatize and executive control demands diminish [?, ?].

We hypothesize that pre-task theta-tACS may reset neural oscillation patterns, lengthen theta cycles to accommodate more gamma activity, and help establish optimal memory strategies during early task phases. After practice, however, frontoparietal activation decreases, memory strategies become automated (e.g., consistently memorizing three items), and theta oscillations stabilize. Stimulation at this stage may no longer adjust theta cycle length but instead enhance theta-gamma phase-amplitude coupling (PAC) to optimize gamma neuron synchrony and activation strength [?, ?], thereby improving memory precision.

No study has directly tested this timing variable, and most research relies on traditional metrics (e.g., n-back tasks) that cannot reveal resource allocation mechanisms. The recall-report paradigm proposed by Zhang & Luck (2008) decomposes WM capacity into independent indices of quantity (number of items remembered) and precision (accuracy of representations). This dynamic trade-off between quantity and precision [?, ?, ?] better reflects resource allocation strategies [?, ?]. For instance, Guo et al. (2021) employed this paradigm with post-practice tACS stimulation, finding that 4 Hz tACS improved memory precision without changing quantity across high- and low-capacity individuals. This aligns with our post-task stimulation hypothesis, though that study did not examine pre-task stimulation. The present research therefore provides the first systematic investigation of how stimulation timing modulates tACS effects on WM through psychological inertia. We hypothesize that pre-task stimulation reduces individual theta frequency, enabling encoding of more items from task onset and forming an "optimal quantity" strategy, whereas post-task stimulation, applied after strategy automation, enhances gamma amplitude to improve execution efficiency of the existing strategy, manifesting as precision gains.

Specifically, this study manipulates 4 Hz tACS timing relative to task phases to examine whether practice-phase trade-off strategies create psychological inertia and whether such inertia transfers across tasks. In Experiment 1, participants were randomly assigned to pre-stimulation (stimulation-practice-formal) or post-stimulation (practice-stimulation-formal) groups. We predicted that pre-stimulation would improve memory quantity while preserving precision (Hypothesis 1a), whereas post-stimulation would enhance precision without changing quantity (Hypothesis 1b), replicating Guo et al. (2021). Experiment 2 further tested whether these timing effects generalize to new tasks. Participants completed two different tasks (color and orientation, order counterbalanced) with tACS applied after the first task's practice phase. We predicted that the first task would replicate Experiment 1's post-stimulation pattern (Hypothesis 2a), while the second novel task would break cognitive inertia and show the pre-stimulation pattern (Hypothesis 2b).

Experiment 1

Experiment 1 manipulated tACS timing to place participants in different initial memory resource states during the practice phase, thereby examining whether stimulation timing moderates tACS effects on WM. In the pre-stimulation group, participants received tACS before practice, affording greater memory resources from task onset. The post-stimulation group received stimulation only after practice, meaning memory resources were enhanced only after the practice phase concluded.

1.1.1 Experimental Design

The experiment employed a mixed design with 2 (stimulation timing: pre vs. post) × 2 (stimulation type: active vs. sham) × 2 (visual field: left, right). Stimulation timing was a between-subjects factor, while stimulation type and visual field were within-subjects factors.

1.1.2 Participants

A priori power analysis using G*Power with a medium effect size of $f = 0.25$ [**?**, **?**], $\alpha = 0.05$, and power = 0.95 indicated a minimum sample size of 36. Thirty-six undergraduate and graduate students from Sichuan Normal University (age range: 18–25 years, $M = 18.97 \pm 1.40$; 12 males) participated voluntarily. Participants were randomly assigned to pre-stimulation ($n = 18$) or post-stimulation ($n = 18$) groups. All had normal or corrected-to-normal vision, no color vision deficits, and no neurological or psychiatric disorders. Participants provided informed consent and received monetary compensation. The study was approved by the Sichuan Normal University Ethics Committee (Approval No.: 2024LS06).

1.1.3 Apparatus and Materials

The experimental program was developed in MATLAB. Stimuli were presented on a 23.8-inch monitor (1920$×1080resolution, 60Hzrefreshrate)withagraybackground(luminance : 150cd/m^2).Duringencoding, fourcoloredsquares(0.8°×$0.8° visual angle) appeared on each side of fixation. Colors were randomly selected from a uniform 360° color wheel with minimum hue separation of 30° and minimum center-to-center distance of 2° between items. The recall display featured a color wheel (outer diameter: 8.2°, inner diameter: 6°) with a response radius of 4.5°. Participants viewed the screen from approximately 60 cm in a dimly lit, comfortable room.

1.1.4 Procedure

We adopted the procedure from Guo et al. (2021). As shown in [Figure 1: see original paper], each trial began with a 1000 ms fixation point, followed by a 200 ms arrow cue indicating which side (left or right) to remember. A 300 ms memory array then presented four colored squares on each side. After a 900 ms retention interval, a color wheel appeared for 3000 ms. Placeholders marked the four target locations on the cued side, with the to-be-reported item indicated by a bolded placeholder. Participants used a mouse to select the target color on the wheel, which rotated randomly each trial. The experimental flow is illustrated in [Figure 2: see original paper]. The formal experiment comprised 300 trials.

1.1.5 Transcranial Alternating Current Stimulation

tACS was delivered using a Starstim8 device (Neuroelectrics, Spain). Prior to electrode placement, scalp sites were cleaned with alcohol to reduce impedance. Two 5$×$5 cm saline-soaked sponge electrodes were positioned with the stimulation electrode over right parietal cortex (P4) and the reference electrode over the right supraorbital region. Individual current thresholds were determined for each participant. The maximum intensity was set at 1500 μA (peak-to-peak). In Phase 1, 1500 μA stimulation was administered; if phosphenes or discomfort occurred, intensity was adjusted downward from 1000 μA in 50 μA steps until no adverse sensations were reported. In Phase 2, stimulation used the individually determined threshold. Active stimulation employed 4 Hz sinusoidal current at the participant's threshold intensity, while sham stimulation consisted of brief ramp-up and ramp-down periods to mimic initial sensations. Mean stimulation intensity across participants was 1261.18 ± 196.38 μA. Impedance was maintained below 10 kΩ throughout.

The pre-stimulation group received 10 minutes of tACS before practice (with feedback), followed by the formal experiment with continued stimulation for the remaining 10 minutes. The post-stimulation group completed practice first, then received 20 minutes of continuous tACS during the formal experiment. If stimulation ended before task completion, participants continued until finished. Each participant underwent both active and sham sessions, separated by one week and scheduled at similar times of day. The study used a single-blind design; participants were unaware of stimulation type.

1.2 Data Analysis

For each trial, deviation was calculated as the absolute difference between reported and target values. Three models from the MemToolbox [**?**, **?**] were compared: StandardMixtureModel, SwapModel, and VariablePrecisionModel. Bayesian Information Criterion (BIC) comparisons showed that VariablePrecisionModel outperformed SwapModel (mean ΔBIC = 1.41 for active, 1.59 for sham; 25 participants supported VariablePrecisionModel). However, StandardMixtureModel was superior to VariablePrecisionModel (mean ΔBIC = -2.07 for active, -1.59 for sham; 25 participants supported StandardMixtureModel). We therefore used StandardMixtureModel to estimate parameters m, sd, and g [**?**, **?**]. This model comprises: (1) a mnemonic component producing von Mises-distributed errors with mean m and standard deviation sd (where sd inversely indexes precision), and (2) a guessing component g representing the probability of random responding (lower g indicates greater memory quantity). These parameters are standard in recall-report studies [**?**, **?**, **?**, **?**, **?**].

1.3 Results

Pearson correlations between individual stimulation intensity and g/sd values revealed no significant relationships in either group (all ps > 0.138), confirming that individual differences in stimulation intensity did not affect results.

1.3.1 Pre-Stimulation Group A 2 (stimulation: 4 Hz vs. sham) × 2 (visual field: left vs. right) repeated-measures ANOVA on guess rate (g) revealed a significant main effect of stimulation, $F(1,17) = 5.59$, $p = 0.030$, $\eta_p^2 = 0.25$. Guess rates were lower in the 4 Hz condition (0.39 ± 0.020) than sham (0.42 ± 0.02), $t(17) = -2.37$, $p = 0.030$, Cohen's $d = 0.56$, indicating improved memory quantity. No significant effects emerged for visual field ($F(1,17) = 1.00$, $p = 0.331$) or the interaction ($F(1,17) = 0.75$, $p = 0.400$).

A parallel ANOVA on precision (sd) showed no significant main effect of stimulation, $F(1,17) = 3.66$, $p = 0.073$, $\eta_p^2 = 0.18$, nor significant effects of visual field ($F(1,17) = 0.08$, $p = 0.248$) or the interaction ($F = 1.56$, $p = 0.229$). Thus, pre-task stimulation enhanced memory quantity without affecting precision, supporting Hypothesis 1a.

1.3.2 Post-Stimulation Group The 2 × 2 ANOVA on guess rate (g) revealed no significant main effect of stimulation, $F(1,17) = 0.62$, $p = 0.440$, $\eta_p^2 = 0.04$, and no effects of visual field ($F(1,17) = 0.34$, $p = 0.564$) or the interaction ($F(1,17) = 0.02$, $p = 0.881$).

However, the ANOVA on precision (sd) showed a significant main effect of stimulation, $F(1,17) = 7.13$, $p = 0.016$, $\eta_p^2 = 0.30$. Precision was higher (sd lower) in the 4 Hz condition (17.48 ± 0.47) than sham (19.27 ± 0.69), $t(17) = -2.67$, $p = 0.016$, Cohen's $d = 0.63$. No significant effects emerged for visual field ($F(1, 17) = 0.05$, $p = 0.835$) or the interaction ($F(1, 17) = 0.57$, $p = 0.461$). Thus, post-task stimulation improved memory precision without affecting quantity, supporting Hypothesis 1b.

1.4 Discussion

Experiment 1 used a recall-report paradigm to examine how stimulation timing affects WM performance. Pre-stimulation improved memory quantity while preserving precision (supporting Hypothesis 1a), suggesting that tACS reduced individual theta frequency to accommodate more items. Post-stimulation enhanced precision without changing quantity (supporting Hypothesis 1b), indicating that stimulation at this phase did not alter theta frequency but instead boosted gamma amplitude to strengthen memory representations. These results confirm that stimulation timing critically moderates tACS effects on WM.

While Experiment 1 established timing-dependent effects, whether these effects persist across different tasks remained unclear. Experiment 2 addressed this by having each participant complete two distinct tasks. Additionally, given the absence of visual field effects in Experiment 1, this variable was eliminated in Experiment 2.

Experiment 2

Building on Experiment 1, Experiment 2 tested whether stimulation-task sequence effects generalize across tasks. Participants completed practice and formal phases for two tasks, with tACS applied after the first task's practice phase. This made the first task equivalent to Experiment 1's post-stimulation condition and the second task equivalent to the pre-stimulation condition. We predicted that the first task would replicate Experiment 1's post-stimulation results (Hypothesis 2a) and the second task would replicate the pre-stimulation pattern (Hypothesis 2b).

2.1.1 Experimental Design

Given the null effect of visual field in Experiment 1, this variable was removed. The design was 2 (task order: color-orientation vs. orientation-color) × 2 (stimulation type: active vs. sham), with task order as a between-subjects factor and stimulation type as a within-subjects factor.

2.1.2 Participants

Power analysis using G*Power with medium effect size $d = 0.5$ [?, ?], $\alpha = 0.05$, and power = 0.80 indicated a minimum of 28 participants per group. Fifty-six university students (12 males; age range: 17–28 years, $M = 20.96$, $SD = 2.89$) participated. None had prior experience with recall-report paradigms, color blindness, or psychiatric/neurological disorders. Participants were randomly assigned to two order groups (n = 28 each) with six males per group. All provided informed consent and received compensation. The study was approved by the Sichuan Normal University Ethics Committee (Approval No.: 2024LS06).

2.1.3 Apparatus and Materials

The experiment was programmed using PsychoToolbox in MATLAB. Stimuli were presented on a 23.8-inch monitor (1920$×$1080 resolution, 60 Hz refresh rate) with a gray background (luminance: 150 cd/m^2). Participants were tested in a comfortable, climate-controlled room at approximately 60 cm viewing distance. The experiment comprised two sessions separated by at least one week, scheduled at similar times of day. Each session included practice (40 trials with feedback) and formal phases (200 trials without feedback, divided into five blocks of 40 trials) for both color and orientation tasks.

2.1.4 Procedure

Participants completed color and orientation recall tasks in counterbalanced order. The color task [Figure 4: see original paper] began with a 1000 ms fixation, followed by a 300 ms memory array presenting two colored squares (0.8°$×$0.8°) on each side of fixation (minimum center-to-center distance: 2.5°). Colors were randomly selected from a 360° color wheel with minimum hue separation of 30°. After a 900 ms retention interval, a recall wheel (outer diameter: 16°, inner diameter: 12°, response radius: 4.5°) appeared at the target location. The wheel rotated randomly each trial, and participants selected the target color using a mouse without time pressure.

The orientation task [Figure 4: see original paper] followed a similar structure. The memory array presented two black rectangular lines (2.2°$×0.5°, *luminance* : 1*cd*/*m*²)*oneachsideat*2.5°*eccentricity*.*Orientationswererandomlyselectedfrom*10°–1
ringcircle(*outerdiameter* : 3.5°, *innerdiameter* : 2.2°)*appearedatthetargetlocation*, *containingtwodiagonalho*
that rotated with mouse movement. Participants adjusted the orientation to match the remembered line and clicked the right mouse button to register their response.

2.1.5 Transcranial Alternating Current Stimulation

Electrode placement followed Experiment 1. Active stimulation used 4 Hz sinusoidal current starting at 1500 μA peak amplitude. If phosphenes or discomfort occurred, intensity was reduced in 50 μA increments until sensations disappeared. Sham stimulation involved 30 s ramp-up and ramp-down periods at the same locations to mimic sensations. Mean stimulation intensity was 1341.07 ± 200.49 μA. After task instructions and practice with performance feedback, stimulation commenced and lasted 37 minutes total.

2.2 Data Analysis

Model comparison using BIC showed that SwapModel outperformed VariablePrecisionModel (mean ΔBIC = -0.71 for active, -1.38 for sham; 31 participants supported SwapModel). StandardMixtureModel was superior to SwapModel (mean ΔBIC = -2.08 for active, -0.68 for sham; 42 participants supported StandardMixtureModel), which was therefore used for fitting. Systematic error distributions fell within acceptable ranges and were not modeled further. Paired t-tests compared g and sd values between stimulation conditions.

2.3 Results

Correlations between stimulation intensity and g/sd values were non-significant across conditions (all ps > 0.053), ruling out intensity confounds.

For the first task, precision (sd) was significantly better (lower) in the 4 Hz condition (20.66 ± 4.91) than sham (22.03 ± 4.87), $t(55) = -2.50$, $p = 0.015$, Cohen's $d = -0.33$. However, guess rate (g) did not differ between conditions, $t(55) = -0.39$, $p = 0.697$, Cohen's $d = -0.05$. Thus, post-practice stimulation improved precision without affecting quantity, replicating Experiment 1's post-stimulation group (supporting Hypothesis 2a).

For the second task, precision (sd) showed no difference between conditions, $t(55) = 1.62$, $p = 0.111$, Cohen's $d = 0.22$. Critically, guess rate (g) was significantly lower in the 4 Hz condition (0.15 ± 0.11) than sham (0.19 ± 0.13), $t(55) = -3.16$, $p = 0.003$, Cohen's $d = -0.42$, indicating improved memory quantity. This pattern matched Experiment 1's pre-stimulation group (supporting Hypothesis 2b).

General Discussion

This study investigated how tACS timing affects WM modulation and whether these effects persist across new tasks. When tACS preceded new task practice, it reduced theta frequency and increased gamma cycle number, enabling participants to enhance memory quantity while maintaining precision (Experiment 1 pre-stimulation group; Experiment 2 second task). Conversely, post-practice stimulation yielded different results: after brief practice, individuals formed stable memory strategies. Even with low-frequency tACS, memory quantity remained unchanged while precision improved (Experiment 1 post-stimulation group; Experiment 2 first task).

Similar timing-dependent effects have been observed in long-term memory research, where pre-task tACS enhanced word-pair memory but stimulation during task performance showed no benefit [**?**, **?**]. From a neurophysiological perspective, pre-task 4 Hz tACS reduces individual theta frequency, lengthening cycles to accommodate more gamma cycles and increase item capacity. Post-task stimulation, applied when theta frequency has stabilized, does not increase cycle length but enhances gamma amplitude through strengthened theta-gamma PAC

[?, ?], improving recall precision. This aligns with findings that tACS effects depend on brain state—alpha-tACS more effectively modulates visual cortex activity when spontaneous alpha is weak (eyes open) than when it is strong (eyes closed) [?, ?]. When task contexts change, the gamma oscillations representing items in the first task (e.g., colors) become inadequate for the new task (e.g., orientations), requiring the nervous system to dynamically adjust theta cycle length to match new encoding demands. Thus, novel tasks prompt individuals to re-evaluate their resources and form new trade-off strategies.

From a psychological inertia perspective, repeated practice strengthens associations between contextual representations and behavioral responses, activating automated strategies when contexts recur [?, ?]. After multiple practice trials, the formal experiment's identical context automatically triggers the practiced resource allocation strategy, making quantity difficult to change regardless of stimulation. However, when completing the second task, participants did not transfer the first task's strategy because behavioral repetition requires stable contexts [?, ?]. The changed task context in Experiment 2's second task prompted resource reallocation based on new demands, leading to new strategy formation. These results demonstrate cognitive flexibility—individuals can adjust memory strategies according to task context rather than rigidly maintaining previous patterns.

Effect sizes for our dependent variables ranged from 0.334 to 0.629, indicating medium effects [?, ?] and robust experimental manipulation. This range parallels meta-analytic findings of WM impairments in schizophrenia ($d = 0.452$) [?, ?]. The guess rate (g) reflects random responding probability, with increases potentially indicating lost representations or excessive memory load. Precision (sd) indexes representational fidelity, with increases reflecting elevated neural noise or impaired binding [?, ?]. These parameters have clinical relevance: Parkinson's patients show reduced WM precision that normalizes after three months of dopaminergic medication [?, ?], and aging affects both parameters—older adults exhibit higher guess rates and lower precision than young adults [?, ?], attributable to reduced neural specificity and inhibitory control. Future research should explore these metrics as diagnostic or intervention-evaluation tools.

tACS holds broad therapeutic promise for improving attention, memory, perception, and emotional regulation in psychiatric and neurological conditions [?, ?]. Studies demonstrate potential applications in neurodegenerative diseases (Alzheimer's, Parkinson's), psychiatric disorders (schizophrenia, depression, insomnia), and chronic pain \cite{Antal & Paulus, 2013; Elyamany et al., 2021; zhang & li, 2022}. Schizophrenia patients receiving theta-tACS during n-back tasks showed WM, processing speed, and attention improvements lasting 50 days [?, ?]. Our findings have important implications: stimulation-task timing critically determines tACS efficacy, and inappropriate timing may obscure therapeutic effects. Clinical applications must carefully consider when stimulation is administered relative to cognitive training or rehabilitation activities.

Several limitations warrant mention. First, methodological differences between experiments—such as intensity titration procedures and the presence of precues in Experiment 1—may introduce subtle variations. Future studies should use individual head modeling (e.g., SimNIBS, ROAST) to control stimulation parameters precisely. Second, feedback during practice allowed participants to monitor strategy effectiveness, but its absence during formal phases may have reinforced practice-phase strategies. This feedback variable should be controlled in future research. Finally, participants in post-stimulation conditions may have been unaware that tACS could augment resources. Explicitly informing participants about resource enhancement might prompt strategy revision, a question requiring further investigation.

In conclusion, pre-task tACS enhances WM quantity, post-task tACS improves precision, and these effects are flexible rather than fixed, with individuals reconstructing strategies when encountering new tasks to maximize resource utilization.

References

Alós-Ferrer, C., Hügelschäfer, S., & Li, J. (2016). Inertia and Decision Making. *Frontiers in Psychology*, *7*, 169. https://doi.org/10.3389/fpsyg.2016.00169

Antal, A., Boros, K., Poreisz, C., Chaieb, L., Terney, D., & Paulus, W. (2008). Comparatively weak after-effects of transcranial alternating current stimulation (tACS) on cortical excitability in humans. *Brain Stimulation*, *1*(2), 97–105. https://doi.org/10.1016/j.brs.2007.10.001

Antal, A., & Paulus, W. (2013). Transcranial alternating current stimulation (tACS). *Frontiers in Human Neuroscience*, *7*, 317. https://doi.org/10.3389/fnhum.2013.00317

Axmacher, N., Henseler, M. M., Jensen, O., Weinreich, I., Elger, C. E., & Fell, J. (2010). Cross-frequency coupling supports multi-item working memory in the human hippocampus. *Proceedings of the National Academy of Sciences*, *107*(7), 3228–3233. https://doi.org/10.1073/pnas.0911531107

Baddeley, A. (2012). Working Memory: Theories, Models, and Controversies. *Annual Review of Psychology*, *63*(1), 1–29. https://doi.org/10.1146/annurev-psych-120710-100422

Barton, B., Ester, E. F., & Awh, E. (2009). Discrete resource allocation in visual working memory. *Journal of Experimental Psychology: Human Perception and Performance*, *35*(5), 1359–1367. https://doi.org/10.1037/a0015792

Bays, P. M., & Husain, M. (2008). Dynamic Shifts of Limited Working Memory Resources in Human Vision. *Science*, *321*(5890), 851–854. https://doi.org/10.1126/science.1158023

Bender, M., Romei, V., & Sauseng, P. (2019). Slow Theta tACS of the Right Parietal Cortex Enhances Contralateral Visual Working Memory Capacity. *Brain Topography*, *32*(3), 477–481. https://doi.org/10.1007/s10548-019-00702-2

Biel, A. L., Sterner, E., Röll, L., & Sauseng, P. (2022). Modulating verbal working memory with fronto-parietal transcranial electric stimulation at theta frequency: Does it work? *European Journal of Neuroscience*, *55*(2), 405–425. https://doi.org/10.1111/ejn.15563

Cohen, J. (1988). *Statistical Power Analysis for the Behavioral Sciences* (2nd ed.). Hillsdale, NJ: Lawrence Erlbaum Associates.

Danner, U. N., Aarts, H., & Vries, N. K. (2008). Habit vs. intention in the prediction of future behaviour: The role of frequency, context stability and mental accessibility of past behaviour. *British Journal of Social Psychology*, *47*(2), 245–265. https://doi.org/10.1348/014466607X230876

Ding, J. (2023). Modulation of working memory capacity on predictive processing during language comprehension. *Language, Cognition and Neuroscience*, *38*(8), 1133–1152.

Elyamany, O., Leicht, G., Herrmann, C. S., & Mulert, C. (2021). Transcranial alternating current stimulation (tACS): From basic mechanisms towards first applications in psychiatry. *European Archives of Psychiatry and Clinical Neuroscience*, *271*(1), 135–156. https://doi.org/10.1007/s00406-020-01209-9

Ericsson, K. A., & Kintsch, W. (1995). Long-term working memory. *Psychological Review*, *102*(2), 211–245. https://doi.org/10.1037/0033-295x.102.2.211

Guo, X., Li, Z., Zhang, L., & Liu, Q. (2021). Modulation of Visual Working Memory Performance via Different Theta Frequency Stimulations. *Brain Sciences*, *11*(10), 1358. https://doi.org/10.3390/brainsci11101358

Haggar, P., Whitmarsh, L., & Skippon, S. M. (2019). Habit discontinuity and student travel mode choice. *Transportation Research Part F: Traffic Psychology and Behaviour*, *64*, 1–13. https://doi.org/10.1016/j.trf.2019.04.022

Jaušovec, N., Jaušovec, K., & Pahor, A. (2014). The influence of theta transcranial alternating current stimulation (tACS) on working memory storage and processing functions. *Acta Psychologica*, *146*, 1–6. https://doi.org/10.1016/j.actpsy.2013.11.011

Jensen, O., & Lisman, J. E. (1998). An Oscillatory Short-Term Memory Buffer Model Can Account for Data on the Sternberg Task. *The Journal of Neuroscience*, *18*(24), 10688–10699. https://doi.org/10.1523/jneurosci.18-24-10688.1998

Jensen, O., & Lisman, J. E. (2005). Hippocampal sequence-encoding driven by a cortical multi-item working memory buffer. *Trends in Neurosciences*, *28*(2), 67–72. https://doi.org/10.1016/j.tins.2004.12.001

Jensen, O., & Mazaheri, A. (2010). Shaping Functional Architecture by Oscillatory Alpha Activity: Gating by Inhibition. *Frontiers in Human Neuroscience*, *4*, 186. https://doi.org/10.3389/fnhum.2010.00186

Jones, K. T. (2019). Replacing tDCS with theta tACS provides selective, but not general WM benefits. *Brain Research*, *1720*, 146317.

Kleinert, M.-L., & Müller, V. (2017). Frequency-Unspecific Effects of θ-tACS Related to a Visuospatial Working Memory Task. *Frontiers in Human Neuroscience*, *11*, 367.

Lee, J., & Park, S. (2005). Working Memory Impairments in Schizophrenia: A Meta-Analysis. *Journal of Abnormal Psychology*, *114*(4), 599–611. https://doi.org/10.1037/0021-843X.114.4.599

Lega, B., Burke, J., Jacobs, J., & Kahana, M. J. (2016). Slow-Theta-to-Gamma Phase–Amplitude Coupling in Human Hippocampus Supports the Formation of New Episodic Memories. *Cerebral Cortex*, *26*(1), 268–278. https://doi.org/10.1093/cercor/bhu232

Liu, C.-L., & Zhou, R.-L. (2013). Effects of Working Memory Training on Cognition and Brain Plasticity. *Advances in Psychological Science*, *20*(7), 1003–1011. https://doi.org/10.3724/sp.j.1042.2012.01003

Long, F., Ye, C., Li, Z., Tian, Y., & Liu, Q. (2020). Negative emotional state modulates visual working memory in the late consolidation phase. *Cognition and Emotion*, *34*(8), 1646–1663. https://doi.org/10.1080/02699931.2020.1795626

Nissim, N. R., McAfee, D. C., Edwards, S., Prato, A., Lin, J. X., Lu, Z., Coslett, H. B., & Hamilton, R. H. (2023). Efficacy of Transcranial Alternating Current Stimulation in the Enhancement of Working Memory Performance in Healthy Adults: A Systematic Meta-Analysis. *Neuromodulation: Technology at the Neural Interface*, *26*(4), 728–737. https://doi.org/10.1016/j.neurom.2022.12.014

Nitsche, M. A., Cohen, L. G., Wassermann, E. M., Priori, A., Lang, N., Antal, A., Paulus, W., Hummel, F., Boggio, P. S., Fregni, F., & Pascual-Leone, A. (2008). Transcranial direct current stimulation: State of the art 2008. *Brain Stimulation*, *1*(3), 206–223. https://doi.org/10.1016/j.brs.2008.06.004

Ouellette, J. A., & Wood, W. (1998). Habit and Intention in Everyday Life: The Multiple Processes by Which Past Behavior Predicts Future Behavior. *Psychological Bulletin*, *124*(1), 54–74.

Paßmann, S., Baselgia, S., Kasten, F. H., Herrmann, C. S., & Rasch, B. (2024). Differential online and offline effects of theta-tACS on memory encoding and retrieval. *Cognitive, Affective, & Behavioral Neuroscience*, *24*(5), 894–911. https://doi.org/10.3758/s13415-024-01204-w

Peich, M.-C., Husain, M., & Bays, P. M. (2013). Age-related decline of precision and binding in visual working memory. *Psychology and Aging*, *28*(3), 729–743. https://doi.org/10.1037/a0033236

Pupíková, M., Maceira-Elvira, P., Harquel, S., Šimko, P., Popa, T., Gajdoš, M., Lamoš, M., Nencha, U., Mitterová, K., Šimo, A., Hummel, F. C., & Rektorová, I. (2024). Physiology-inspired bifocal frontoparietal tACS for working memory enhancement. *Heliyon*, *10*(18), e37427. https://doi.org/10.1016/j.heliyon.2024.e37427

Riecke, L., Formisano, E., Herrmann, C. S., & Sack, A. T. (2015). 4-Hz Transcranial Alternating Current Stimulation Phase Modulates Hearing. *Brain Stimulation*, *8*(4), 777–783. https://doi.org/10.1016/j.brs.2015.04.004

Ruhnau, P., Neuling, T., Fuscá, M., Herrmann, C. S., Demarchi, G., & Weisz, N. (2016). Eyes wide shut: Transcranial alternating current stimulation drives alpha rhythm in a state dependent manner. *Scientific Reports*, *6*(1), 27138. https://doi.org/10.1038/srep27138

Samuelson, W., & Zeckhauser, R. (1988). Status quo bias in decision making. *Journal of Risk and Uncertainty*, *1*(1), 7–59. https://doi.org/10.1007/BF00055564

Sawilowsky, S. S. (2009). New Effect Size Rules of Thumb. *Journal of Modern Applied Statistical Methods*, *8*(2), 597–599. https://doi.org/10.22237/jmasm/1257035100

Schneegans, S., & Bays, P. M. (2017). Neural Architecture for Feature Binding in Visual Working Memory. *The Journal of Neuroscience*, *37*(14), 3913–3925. https://doi.org/10.1523/JNEUROSCI.3493-16.2017

Shiffrin, R. M., & Schneider, W. (1977). Controlled and automatic human information processing: II. Perceptual learning, automatic attending and a general theory. *Psychological Review*, *84*(2), 127–190. https://doi.org/10.1037/0033-295x.84.2.127

Spitzer, B., & Blankenburg, F. (2011). Stimulus-dependent EEG activity reflects internal updating of tactile working memory in humans. *Proceedings of the National Academy of Sciences*, *108*(20), 8444–8449. https://doi.org/10.1073/pnas.1104189108

Sreeraj, V. S., Shivakumar, V., Sowmya, S., Bose, A., Nawani, H., Narayanaswamy, J. C., & Venkatasubramanian, G. (2019). Online Theta Frequency Transcranial Alternating Current Stimulation for Cognitive Remediation in Schizophrenia: A Case Report and Review of Literature. *The Journal of ECT*, *35*(2), 139–143. https://doi.org/10.1097/yct.0000000000000523

Suchow, J. W., Brady, T. F., Fougnie, D., & Alvarez, G. A. (2013). Modeling visual working memory with the MemToolbox. *Journal of Vision*, *13*(10), 9–9. https://doi.org/10.1167/13.10.9

Sweller, J., J. G. van Merrienboer, J., & G. W. C. Paas, F. (1998). Cognitive Architecture and Instructional Design. *Educational Psychology Review*, *10*(3), 251–296.

Tavakoli, A. V., & Yun, K. (2017). Transcranial Alternating Current Stimulation (tACS) Mechanisms and Protocols. *Frontiers in Cellular Neuroscience*, *11*, 214. https://doi.org/10.3389/fncel.2017.00214

Tseng, P. (2018). The critical role of phase difference in theta oscillation between bilateral parietal cortices for visuospatial working memory. *Scientific Reports*, *8*(1), 349.

Vogel, E. K., McCollough, A. W., & Machizawa, M. G. (2005). Neural measures reveal individual differences in controlling access to working memory. *Nature*, *438*(7067), 500–503. https://doi.org/10.1038/nature04171

Wang, S., Itthipuripat, S., & Ku, Y. (2019). Electrical Stimulation Over Human Posterior Parietal Cortex Selectively Enhances the Capacity of Visual Short-Term Memory. *The Journal of Neuroscience*, *39*(3), 528–536. https://doi.org/10.1523/JNEUROSCI.1959-18.2018

Wolinski, N., Cooper, N. R., Sauseng, P., & Romei, V. (2018). The speed of parietal theta frequency drives visuospatial working memory capacity. *PLOS Biology*, *16*(3), e2005348. https://doi.org/10.1371/journal.pbio.2005348

Ye, C., Hu, Z., Li, H., Ristaniemi, T., Liu, Q., & Liu, T. (2017). A two-phase model of resource allocation in visual working memory. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *43*(10), 1557–1566. https://doi.org/10.1037/xlm0000376

Ye, C., Sun, H.-J., Xu, Q., Liang, T., Zhang, Y., & Liu, Q. (2019). Working memory capacity affects trade-off between quality and quantity only when stimulus exposure duration is sufficient: Evidence for the two-phase model. *Scientific Reports*, *9*(1), 8727. https://doi.org/10.1038/s41598-019-44998-3

zhang siyuan, & li xuebing. (2022). The application of different frequencies of transcranial alternating current stimulation in mental disorders. *Advances in Psychological Science*, *30*(9), 2053. https://doi.org/10.3724/sp.j.1042.2022.02053

Zhang, D.-W., Moraidis, A., & Klingberg, T. (2022). Individually tuned theta HD-tACS improves spatial performance. *Brain Stimulation*, *15*(6), 1439–1447. https://doi.org/10.1016/j.brs.2022.10.009

Zhang, & Luck, S. J. (2008). Discrete fixed-resolution representations in visual working memory. *Nature*, *453*(7192), 233–235. https://doi.org/10.1038/nature06860

Zhang, X., Wang, W., Duan, H., Zhao, Y., Kan, Y., & Hu, W. (2019). Effect of Working Memory on Insight and Analytic Problem Solving. *Journal of Psychological Science*, *42*(4), 777–783.

Zokaei, N., Burnett Heyes, S., Gorgoraptis, N., Budhdeo, S., & Husain, M. (2015). Working memory recall precision is a more sensitive index than span. *Journal of Neuropsychology*, *9*(2), 319–329. https://doi.org/10.1111/jnp.12052

Note: Figure translations are in progress. See original paper for figures.