

The impact of tACS stimulation timing on the modulation of working memory

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Abstract

Previous studies have demonstrated that tACS (transcranial alternating current stimulation) can expand cognitive resources, thereby improving working memory (WM) performance, while some studies failed to observe a definitive advantage of tACS in boosting WM. Regarding this ongoing debate, this study sought to explore the effect of tACS on working memory by involving the factor of psychological inertia. Psychological inertia refers to the unconscious, automatic behavior of an individual. The conflict between psychological inertia and rational decision-making could lead to a loss of optimal choice.

In Experiment 1, 36 participants completed a color recall reporting task. Active or sham tACS was applied before or after practice to manipulate the amount of memory resources at the initial stage. The results confirmed our hypothesis that participants who received active tACS after practice (post-practice) adopted similar memory strategies to those receiving sham stimulation due to a psychological inertia. They exhibited a trade-off between quantity and quality, i.e., post-practice tACS could boost memory accuracy with comparable quantity; while pre-practice stimulation improved memory quantity with comparable accuracy.

To investigate whether the regulatory effects of the first task would carry over to the second task, 56 participants completed both color and orientation recall reporting tasks in Experiment 2, where tACS stimulation was applied after the practice of the first task. The results revealed that memory accuracy was improved while the quantity was unchanged in the first task, which is consistent with the results from the group receiving post-practice tACS in Experiment 1. However, the memory quantity was enhanced and the accuracy was kept unchanged in the second task, consistent with the results of pre-practice tACS in Experiment 1. This indicates that, psychological inertia can be disrupted in new situations, leading to new strategies.

The regulatory effects of tACS on WM are modulated by the timing of stimulation. That is, pre-practice tACS influences the memory quantity, and post-practice tACS affects memory accuracy. Furthermore, the regulatory effects that were established during the first task may be disrupted when encountering a new task. These findings clarify the optimal temporal window for tACS intervention, providing a precise reference for clinical cognitive rehabilitation, such as early intervention in Alzheimer's disease.

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

1 Introduction

Visual working memory (VWM) is a core component of cognitive function, responsible for the brief retention, manipulation, and storage of visual information. Studies have shown that individuals with high VWM capacity outperform those with low capacity in tasks such as problem solving (Zhang et al., 2019), language comprehension (Ding et al., 2023), and inhibiting irrelevant information (Vogel et al., 2005). However, there is significant variability in VWM capacity across individuals, and individuals with low VWM capacity may experience limitations in cognitive performance. Consequently, researchers have been exploring effective non-invasive methods to enhance VWM capacity and improve cognitive functioning.

In recent years, transcranial alternating current stimulation (tACS) at theta frequencies has been shown to significantly improve individuals' working memory performance by modulating the neural oscillatory synchronization in the parietal region (Biel et al., 2022). This finding holds substantial clinical

relevance for populations with cognitive decline, such as the elderly (Pupíková et al., 2024). The mechanism of action primarily involves theta-gamma cross-frequency coupling (Jensen & Lisman, 1998, 2005), where one gamma cycle corresponds to a single memory item, and multiple gamma sub-cycles are nested within one theta cycle. As the number of memory items increases, the frequency of the theta wave decreases (Axmacher et al., 2010). tACS delivers weak currents at specific frequencies to synchronize brain oscillations, thereby influencing cognitive performance (Antal et al., 2008; Nitsche et al., 2008; Riecke et al., 2015). Low-frequency tACS (such as 4 Hz) can decrease an individual's brain theta frequency, lengthen the theta cycle, and accommodate more gamma cycles, thereby enhancing working memory capacity. It is important to note that theta-gamma coupling primarily participates in the encoding phase of working memory, while information maintenance depends on alpha (8-12 Hz) and beta (13-30 Hz) oscillations. Studies have shown that alpha oscillations protect working memory representations by suppressing irrelevant brain activity

(Jensen & Mazaheri, 2010), while beta oscillations are involved in the updating and maintenance of memory content (Spitzer & Blankenburg, 2011). This functional segregation suggests that the regulatory effect of theta-tACS may be phase-specific—enhancing information input efficiency during the encoding phase by modulating theta-gamma coupling, with limited effects on the maintenance phase. Therefore, this study focuses on the impact of theta-tACS on working memory capacity, aiming to investigate its specific effects during the encoding phase.

Although the potential of tACS to enhance working memory performance has been recognized, there are inconsistencies in the findings across different studies. For instance, Zhang et al. (2022) found that theta-frequency tACS effectively improved visuospatial working memory performance, while Kleinert et al. (2017) failed to observe an improvement in visuospatial working memory performance with theta-frequency tACS. These contradictions suggest that the modulation effects of tACS may be influenced by multiple factors. A meta-analysis by Nissim et al. (2023) highlighted that task difficulty (Biel et al., 2022) and phase (Tseng et al., 2018) are significant modulatory variables. Some studies have also found that other factors influence the effects of tACS stimulation. For example, under high cognitive load, 4 Hz tACS significantly increased an individual's working memory capacity compared to sham stimulation and high-frequency 7 Hz tACS (Bender et al., 2019), indicating that the frequency of stimulation affects the outcome. Furthermore, the targeted brain region (Jones et al., 2019) also plays a role in the effectiveness of tACS. Stimulation at 4.5 Hz over the right frontal-parietal cortex selectively improved object-based working memory, while tACS over the bilateral frontal cortex had no significant impact on working memory (Jones et al., 2019), suggesting the critical role of the parietal region in working memory (Jaušovec et al., 2014). Additionally, the timing of stimulation may be an important factor. Studies applying pre-task stimulation generally find significant improvements in working memory with synchronous stimulation (Biel et al., 2022; Jones et al., 2019). For instance, Jaušovec's study showed that 15 minutes of tACS stimulation over the parietal region before a task significantly enhanced working memory performance (Jaušovec et al., 2014). However, studies applying post-task stimulation report different trends, with no significant effect on working memory performance when stimulation was applied after the task had already begun (Kleinert et al., 2017).

We hypothesize that this discrepancy may be related to psychological inertia. Psychological inertia refers to an individual's automatic behavioral tendency formed in repeated situations (Haggar et al., 2019). It maintains the coherence of behavior and helps individuals predict future actions (Ouellette & Wood, 1998). However, when psychological inertia conflicts with rational decision-making, it may lead to the neglect of optimal choices and increase decision errors (Alós-Ferrer et al., 2016; Samuelson & Zeckhauser, 1988). This concept resonates with changes in the function of the central executive system in Baddeley's multicomponent model: in the early stages of a task, the central executive system is highly involved in resource allocation and strategy selection, whereas, after the task becomes automated, its involvement diminishes (Ericsson & Kintsch, 1995; Sweller et al., 1998). That is, skilled tasks can be processed automatically by subsidiary systems (such as the phonological loop or the visuospatial sketchpad), reducing the

cognitive load on the central executive system (Baddeley, 2012; Shiffrin & Schneider, 1977). The neural basis for this automation may be a reduction in activation in the frontal-parietal regions. For instance, in the field of working memory training, early learning requires high activation in the frontal-parietal areas to maintain conscious control; however, after training, as the task becomes more automated, the demand for executive control from these regions decreases, leading to reduced activation (Liu et al., 2013).

Therefore, at the early stages of a task, theta-tACS may break the original neural oscillatory patterns by phase resetting, lengthening the theta cycle to accommodate more gamma activity, and thereby assisting in establishing an optimal memory strategy. However, after task practice, when frontal-parietal activation decreases, and memory strategies become automated (e.g., remembering three items), theta oscillations stabilize. In this case, providing stimulation will no longer adjust the theta cycle to accommodate the task but will instead optimize the gamma neuron synchronization and activation intensity through theta-gamma phase-amplitude coupling (PAC) (Lega et al., 2016), thus enhancing the accuracy of memory representations.

However, no study has directly validated the impact of stimulation timing as a variable. Existing studies mainly rely on traditional metrics (such as the n-back task), which are limited in revealing resource allocation mechanisms. The recall-reporting paradigm proposed by Zhang and Luck (2008) divides working memory capacity into two independent metrics: quantity, referring to the number of items an individual can remember in a short period of time, and accuracy, referring to the correctness of the items remembered. Compared to traditional metrics, the dynamic trade-off between quantity and accuracy (Barton et al., 2009; Bays & Husain, 2008) more effectively reflects the resource allocation strategy (Ye et al., 2019). For example, in a study by Guo et al. (2021), participants completed a practice task, followed by tACS stimulation, and then performed a formal experiment. The results showed that under the 4 Hz condition, both high and low capacity participants improved memory accuracy, but memory quantity remained unchanged. This result aligns with the hypothesis regarding post-task stimulation, but does not investigate the “pre-task then stimulation” condition. Therefore, this study will be the first to systematically examine how stimulation timing modulates tACS effects on working memory through psychological inertia.

We hypothesize that applying stimulation before the task will lower an individual's theta frequency, allowing participants to encode more items at the beginning of the task, thereby forming an “optimal memory quantity” strategy. In contrast, applying stimulation after the task has started, when the original strategy has already become automated, will not alter the theta cycle but will regulate gamma amplitude to enhance the execution efficiency of the existing strategy, resulting in accuracy improvement.

Specifically, this study will manipulate 4 Hz tACS stimulation during different stages of the task to examine whether the trade-off strategies formed during the practice phase lead to psychological inertia and whether this inertia can transfer across different tasks. In Experiment 1, participants will be randomly assigned to the pre-stimulation group (stimulus-practice-task) or post-stimulation group (practice-stimulus-task). In the pre-stimulation group, tACS will be applied at the

beginning of the task to lower the theta frequency in the brain. In this group, we hypothesize that, compared to sham stimulation, memory accuracy will remain unchanged, while memory quantity will increase (Hypothesis 1a). Conversely, in the post-stimulation group, the trade-off strategy formed during the practice phase will be subject to inertia, leading to results consistent with those of Guo et al. (2021): memory quantity will remain unchanged, but accuracy will increase (Hypothesis 1b). In Experiment 2, we will further validate the results of Experiment 1 and explore whether theta-tACS can prompt individuals to form new resource allocation strategies when faced with a new task. Participants will complete two different tasks (color and orientation tasks, with random task order), and each participant will receive tACS stimulation after completing the practice phase of the first task. We hypothesize that, when individuals face an entirely new task, theta-tACS, through the phase-resetting mechanism, will break the cognitive inertia formed in the previous task and allow participants to reallocate resources according to the new task's characteristics. Therefore, for the first task, we expect the results to align with those of the post-stimulation group in Experiment 1 (Hypothesis 2a). For the second new task, participants may reconfigure their strategies based on the characteristics of the task, and we anticipate the results to be similar to those of the pre-stimulation group in Experiment 1 (Hypothesis 2b).

2 Experiment 1: The Effect of tACS Stimulation Timing on Working Memory Trade-off Strategies

Experiment 1 aims to manipulate the timing of tACS stimulation to examine whether the timing of stimulation affects its regulatory effects on working memory (WM). In the pre-stimulation group, tACS is applied before the practice phase, thereby providing participants with more memory resources before the task begins. In contrast, the post-stimulation group receives stimulation only after the practice phase, meaning their memory resources are enhanced just before the formal experiment begins.

2.1 Experiment Methods

2.1.1 Experimental Design

The experiment employs a 2 (stimulation timing: pre-stimulation vs. post-stimulation) \times 2 (stimulation type: active stimulation vs. sham stimulation) \times 2 (visual field hemisphere: left, right) mixed design, where stimulation timing is a between-subjects variable, and stimulation type is a within-subjects variable.

2.1.2 Participants

A priori power analysis, with an effect size of $f = 0.25$ (Wolinski et al., 2018), $\alpha = 0.05$, and a statistical power of 0.95, determined that a total sample size of at least 36 participants was required. Thirty-six undergraduate and graduate students from Sichuan Normal University volunteered for the experi-

ment. Their ages ranged from 18 to 25 years, with a mean age of 18.97 ± 1.40 years, including 12 male participants. Participants were randomly assigned to two groups: the pre-stimulation group and the post-stimulation group. All participants had normal or corrected-to-normal vision, no color vision deficiency, and no history of psychiatric disorders. Informed consent was obtained from all participants before the experiment, and they received compensation upon completion. The experiment was approved by the Ethics Committee of Sichuan Normal University (Approval Number: 2024LS06).

2.1.3 Experimental Materials

The experimental procedure was programmed using MATLAB, with stimuli displayed on a 23.8-inch monitor (resolution: 1920×1080 , refresh rate: 60 Hz). The background of the screen was gray, with a brightness of 150° . In the stimulus interface, fixation points were presented on the left and right sides, each accompanied by four memory items. Each memory item was a colored square (viewing angle: $0.8^\circ \times 0.8^\circ$), with colors randomly selected from a uniformly distributed 360° color wheel. The color difference between adjacent squares was at least 30° , and the distance between the centers of the squares was no less than 2° . The recall interface displayed a color wheel with an outer diameter of 8.2° , an inner diameter of 6° , and a target radius of 4.5° . Participants completed the experiment in a room with soft, stable, and comfortable lighting, seated approximately 60 cm from the computer screen.

2.1.4 Experimental Procedure

The experimental procedure followed the design of Guo et al. (2021), with a flowchart shown in Figure 1. The task began with the presentation of a 1000 ms fixation point, followed by a 200 ms arrow pointing left or right to indicate which half of the upcoming memory array (left or right) participants should focus on. Then, a 300 ms memory array was displayed, with four colored squares presented on the left and right. This was followed by a 900 ms retention interval, during which the fixation point remained in the center of the screen. Finally, a color wheel appeared on the screen, with four placeholders placed at the location corresponding to the arrow direction. The placeholder for the target color was highlighted in bold, and participants were instructed to select the target color on the color wheel using a mouse, within a 3000 ms time limit. In each trial, the color wheel would rotate randomly. The color and position of each square were randomly assigned by the computer program. The formal experiment consisted of 300 trials, with the experimental group design flowchart shown in Figure 2.

2.1.5 Transcranial Alternating Current Stimulation (tACS)

In this experiment, transcranial alternating current stimulation (tACS) was applied using the Starstim8 device produced by Neuroelectronics (Spain). Prior to electrode placement, the corresponding scalp regions were cleaned with alcohol swabs to reduce impedance. Two $5 \text{ cm} \times 5 \text{ cm}$ sponge electrodes,

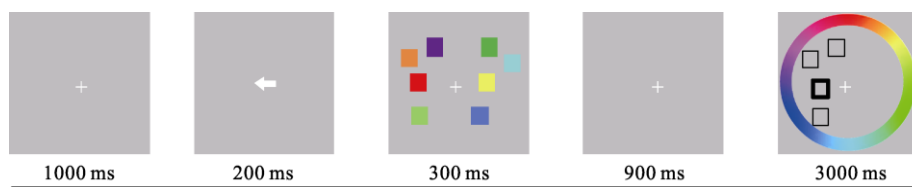


Figure 1 Experimental flowchart. During stimulus presentation, there are 4 color blocks on each side, with each block having a distinct color, and the colors on the left and right sides do not repeat. A color image is available in the electronic version, and the same applies below.

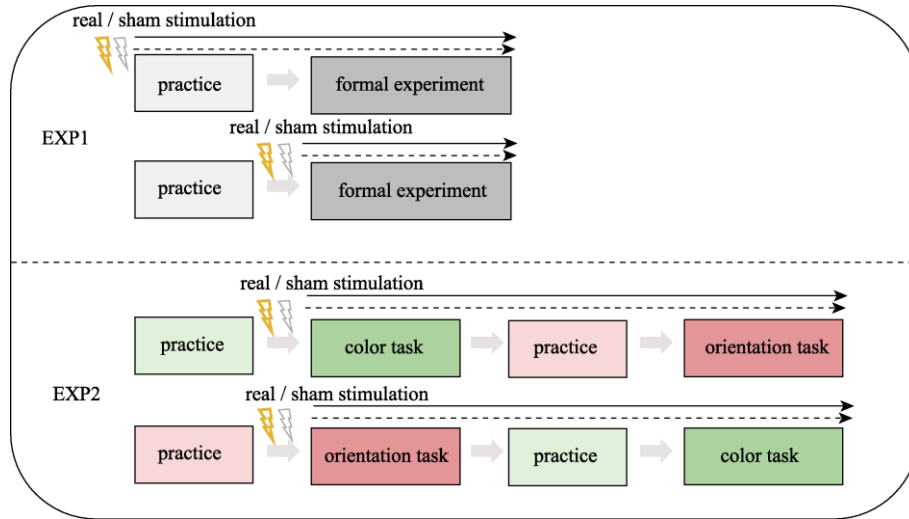


Figure 2. Flowchart of tACS stimulation and task order in Experiments 1 and 2. In Experiment 1, half of the participants were assigned to the pre-stimulation group, and half to the post-stimulation group. Each group completed both real and sham stimulation conditions with a one-week interval. In Experiment 2, half of the participants completed the color task first, and the other half completed the orientation task first. Each participant completed both real and sham stimulation conditions with a one-week interval. Yellow lightning indicates real stimulation, and black lightning indicates sham stimulation. Solid long arrows represent the duration of real stimulation, while dashed long arrows represent the duration of sham stimulation.

soaked in saline, were then placed on the scalp: the stimulation electrode was positioned over the right parietal cortex (P4), and the reference electrode was placed above the right eyebrow. After electrode placement, the individual current threshold for each participant was determined. The initial maximum stimulation intensity was set to 1500 μA .

In the first phase, 1500 μA stimulation was applied, and any sensations such as photic hallucinations or discomfort were monitored. If no such sensations were reported, this intensity was maintained; otherwise, the intensity was reduced starting at 1000 μA , with stepwise increments of 50 μA or decrements of 100 μA , until the highest intensity that did not induce photic hallucinations or abnormal sensations was identified. In the second phase, the current was adjusted according to the threshold established in the first phase.

The stimulation frequency was set to two conditions: 4 Hz active stimulation and sham stimulation. In the 4 Hz active stimulation condition, the stimulation was delivered using the individual's threshold, while the sham stimulation consisted only of brief pulses, designed to simulate the initial sensations induced by active stimulation. The average stimulation intensity for all participants was $1261.18 \pm 196.38 \mu\text{A}$. During the sham stimulation phase, the frequency was maintained at 4 Hz throughout the fade-in, stimulation, and fade-out periods, and participants performed the task only after the fade-in was complete. Throughout all stimulation periods, impedance was kept below 10 k Ω . Both groups of participants received one session of active stimulation and one session of sham stimulation, with the sham stimulation serving as a baseline control, and the sequence of conditions was counterbalanced across participants.

After electrode placement, participants were briefed on the experimental task, which required them to respond using a mouse. The pre-stimulation group first received 10 minutes of stimulation, followed by the practice phase (including feedback), and then the formal experiment, during which the remaining time of stimulation continued until the end of the experiment. The post-stimulation group, on the other hand, first

completed a brief practice task, followed by stimulation and the main experiment. The total tACS stimulation duration for both groups was 20 minutes. If the experiment was not completed before the end of stimulation, the task continued until completion. The same participant underwent both sessions with a one-week interval between experiments, and efforts were made to schedule the sessions at the same time of day. The experiment employed a single-blind design, where participants were unaware of the type of stimulation they received during each phase.

2.2 Data Analysis

In the recall-reporting task, the deviation for each trial was calculated by subtracting the reported value from the target value and taking the absolute value, followed by model fitting. Specifically, three models were compared in MATLAB using the MemToolbox (Suchow et al., 2013): the Standard Mixture Model, the Swap Model, and the Variable Precision Model. The Bayesian Information Criterion (BIC) was used for model comparison. When comparing the Swap Model with the Variable Precision Model (ΔBIC), a negative ΔBIC supports the former model, and a positive ΔBIC supports the latter. The average ΔBIC for active stimulation was 1.41, and for sham stimulation, it was 1.59. A total of 25 participants supported the Variable Precision Model, indicating its superiority over the Swap Model.

Next, the Standard Mixture Model and the Variable Precision Model were compared. The average ΔBIC for active stimulation was -2.07 , and for sham stimulation, it was -1.59 . A total of 25 participants preferred the Standard Mixture Model. Subsequently, the Standard Mixture Model was applied to fit the deviation data, and the model parameters M (mean), SD (standard deviation), and G (guess rate) were obtained (Zhang & Luck, 2008).

The Standard Mixture Model comprises two components: one is the effective memory component. If a memory item is encoded into the participant's memory representation, it results in a deviation that follows a von Mises distribution with a mean

of M and a standard deviation of SD . The difference between the encoded value and the actual value of the item determines the width of the error distribution, which inversely reflects memory accuracy. Therefore, the SD value serves as an indicator of memory accuracy, with smaller SD s indicating higher accuracy. The second component is the guess rate (G). If an item is not remembered, the participant will make a random guess, and the deviation follows a uniform distribution. The guess rate, G , represents the probability that the recalled item appears in the memory representation, with smaller G values indicating greater memory capacity. Hence, G serves as an indicator of memory quantity. This model is widely used in studies employing the recall-reporting paradigm to fit error data (Guo et al., 2021; Long et al., 2020; Wang et al., 2019; Ye et al., 2017).

2.3 Experimental Results

Pearson correlations were conducted between the individual stimulation currents and the G -values and SD -values under different conditions. The results showed that in the pre-stimulation group, the stimulation current strength was not correlated with the SD value ($r(17) = -0.375, p = 0.138$) or the G -value ($r(17) = 0.146, p = 0.575$) under the active stimulation condition, nor with the SD value ($r(17) = -0.14, p = 0.592$) or the G -value ($r(17) = 0.058, p = 0.824$) under the sham stimulation condition. Similarly, in the post-stimulation group, the stimulation current strength was not correlated with the SD value ($r(17) = -0.268, p = 0.283$) or the G -value ($r(17) = -0.301, p = 0.224$) under the active stimulation condition, nor with the SD value ($r(17) = 0.113, p = 0.655$) or the G -value ($r(17) = -0.111, p = 0.661$) under the sham stimulation condition. These findings indicate that the differences in stimulation current received by each participant did not affect the experimental outcomes.

2.3.1 Pre-Stimulation Group

A 2×2 repeated-measures ANOVA was conducted to analyze the G -values of the pre-stimulation group, with stimulation condition (4 Hz vs. sham) and visual field (left vs. right) as factors. The results showed a significant main effect of the stimulation condition (Figure 3), $F(1, 17) = 5.59, p = 0.030, \eta_p^2 = 0.25$, where the guess rate under 4 Hz stimulation (0.39 ± 0.020) was lower than under sham stimulation (0.42 ± 0.02), $t(17) = -2.37, p = 0.030$, Cohen's $d = 0.56$. This suggests that in the pre-stimulation group, 4 Hz tACS increased the number of items in working memory compared to sham stimulation.

The main effect of visual field was not significant, $F(1, 17) = 1.00, p = 0.331$; the interaction effect between visual field and stimulation condition was also not significant, $F(1, 17) = 0.75, p = 0.400$.

A 2×2 repeated-measures ANOVA was also performed on the SD -values of the pre-stimulation group. The results showed that the main effect of the stimulation condition was not significant, $F(1, 17) = 3.66, p = 0.073$; the main effect of visual field was not significant, $F(1, 17) = 0.08, p = 0.248$; the interaction between visual field and stimulation condition was also not significant, $F = 1.56, p = 0.229$. This indicates that pre-stimulation does not significantly improve the memory accuracy of participants.

2.3.2 Post-Stimulation Group

A 2×2 repeated-measures ANOVA was conducted to analyze the G -values of the post-stimulation group, with stimulation condition (4 Hz vs. sham) and visual field (left vs. right) as factors. The results (Figure 3) revealed that the main effect of the stimulation condition was not significant, $F(1, 17) = 0.62, p = 0.440$; the main effect of visual field was not significant, $F(1, 17) = 0.34, p = 0.564$; and the interaction between visual field and stimulation condition was also not significant, $F(1, 17) = 0.02, p = 0.881$.

A 2×2 repeated-measures ANOVA was also performed on the SD -values of the post-stimulation group. The results showed a significant main effect of the stimulation condition, $F(1, 17) = 7.13, p = 0.016, \eta_p^2 = 0.30$; the SD -value under 4 Hz stimulation (17.48 ± 0.47) was lower than under sham stimulation (19.27 ± 0.69), $t(17) = -2.67, p = 0.016$, Cohen's $d = 0.63$. This suggests that in the post-stimulation group, 4 Hz tACS improves the memory accuracy compared to sham stimulation. The main effect of visual field was not significant, $F(1, 17) = 0.05, p = 0.835$; and the interaction between visual field and stimulation condition was also not significant, $F(1, 17) = 0.57, p = 0.461$.

Experiment 1 utilized the recall-reporting paradigm, dividing participants into two groups that received different sequences of stimulation and tasks to explore the variations in their working memory performance. The results indicated that, under the pre-stimulation condition, compared to the sham stimulation group, the true stimulation group had unchanged memory accuracy but an increased memory quantity (supporting Hypothesis 1a). This suggests that tACS stimulation lowers

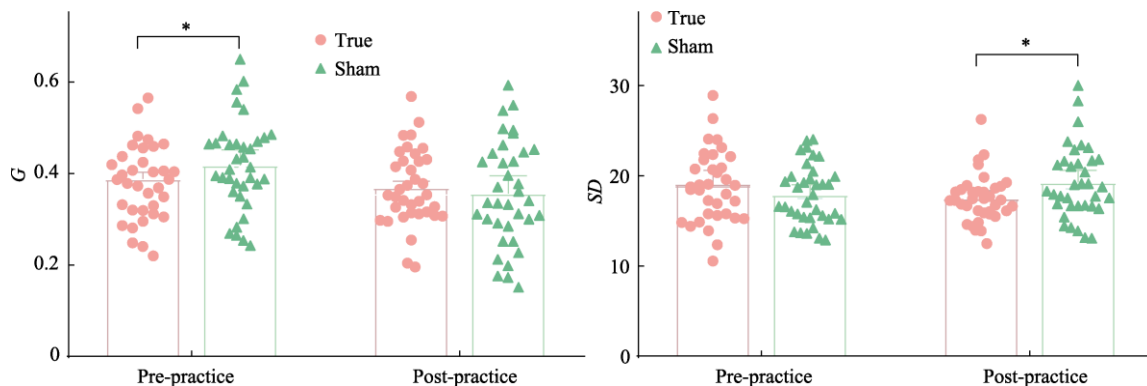


Figure 3. The left part of the figure shows the guess rate G results for the pre-stimulation and post-stimulation groups (data from both left and right visual fields combined). The right part shows the accuracy SD results for the pre-stimulation and post-stimulation groups. Note: Larger G values indicate a lower working memory capacity, and higher SD values indicate poorer working memory accuracy. In both G and SD results, circles represent real stimulation conditions, and triangles represent sham stimulation conditions.

the individual's brain theta frequency, enhancing the number of items stored in memory. Conversely, under the post-stimulation condition, compared to the sham stimulation group, the true stimulation group had unchanged memory quantity but improved memory accuracy (supporting Hypothesis 1b), indicating that the tACS stimulation at this stage did not lower theta frequency but instead enhanced gamma amplitude, improving the precision of memory representation. In conclusion, the results of Experiment 1 demonstrate that the timing of stimulation relative to the task influences the effect of tACS on working memory.

While Experiment 1 confirmed the effect of tACS and task order on working memory modulation, it remains unclear whether this effect will generalize to other tasks. Therefore, in Experiment 2, each participant will complete two different tasks. Furthermore, since no significant effect of visual field was observed in Experiment 1, this variable will be removed in Experiment 2.

3 Experiment 2: The Effect of tACS Stimulation on Strategy Modulation Does Not Transfer to a New Task

Experiment 2 builds upon Experiment 1 to further validate whether the effect of stimulation timing and task order on tACS modulation generalizes to other tasks. Specifically, participants will complete two tasks in sequence: a color recall task and an orientation recall task. The stimulation will be applied during the practice phase of the first task, which corresponds to the post-practice stimulation condition from Experiment 1 for the first task. For the second task, the stimulation condition will match the pre-practice stimulation condition from Experiment 1. We expect the results of the first and second tasks to align with the post- and pre-practice stimulation conditions, respectively, from Experiment 1.

3.1 Experimental Methods

3.1.1 Experimental Design

Since Experiment 1 showed that the visual field half does not affect the results, this variable will be removed in Experiment 2. The experiment follows a 2 (Order: Color–Orientation vs. Orientation–Color) \times 2 (Stimulation Type: Active vs. Sham) mixed design, where order is a between-subjects variable, and stimulation type is a within-subjects variable.

3.1.2 Participants

A priori power analysis using G*Power software was conducted to determine the required sample size. Using a medium effect size of $d = 0.5$ (Cohen, 1988), $\alpha = 0.05$, and statistical power of 0.8, the analysis indicated that each group should have at least 28 participants. In total, 56 undergraduate students (12 male) from Sichuan Normal University participated in the study. Participants were aged between 17 and 28 years ($M = 20.96$, $SD = 2.89$). All participants had no apparent intellectual disabilities, normal or corrected-to-normal vision, no color blindness or color vision deficiencies, no psychiatric history, and no prior exposure to the recall-reporting paradigm. Participants were randomly assigned to two order groups, with each order group including six male participants. Before the experiment, each participant carefully read and signed the informed consent form, and they were compensated based on their effort upon completing the study. The study was approved by the Ethics Committee of Sichuan Normal University (Approval number: 2024LS06).

3.1.3 Experimental Materials and Procedure

The experimental procedure was written in MATLAB using the PsychoToolbox toolbox. Stimuli were presented on a 23.8-inch monitor with a resolution of 1920 \times 1080 pixels and a 60 Hz refresh rate. The background was gray, with a luminance of 150°. Participants sat in a comfortable, cool laboratory approximately 60 cm from the screen. The experiment was divided into two phases, with at least one week between phases, and efforts were made to ensure that participants completed both phases at the same time of day. Each phase included practice and formal tasks for both the color recall task and the orientation recall task. The practice tasks consisted of 40 trials each, with feedback provided after each trial. The formal tasks included 200 trials each, with no feedback provided for errors. The formal tasks were divided into 5 blocks, each containing 40 trials.

3.1.4 Experimental Procedure

Participants completed the practice and formal tasks for color recall and orientation recall in sequence, with the order of tasks randomized. Half of the participants started with the color task, while the other half started with the orientation task.

For the Color Recall Reporting Task (as shown in Figure 4), the experiment began with a 1000 ms fixation point, followed

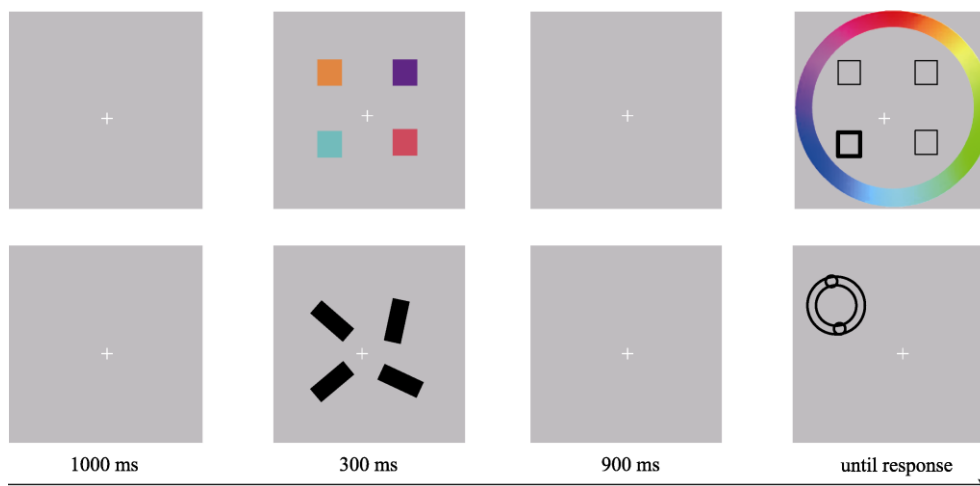


Figure 4. Flowchart of color and orientation recall tasks. In the color task, 4 different colors are presented at 4 positions.

by a 300 ms memory array. Two colored squares were presented on each side (left and right) of the screen, with each square subtending a visual angle of $0.8^\circ \times 0.8^\circ$. The distance between the centers of the squares was at least 2.5° . The colors of the squares were randomly selected from a 360° color wheel with a minimum color difference of 30° between the selected colors. After the memory array, a 900 ms retention interval followed. In the recall phase, a color ring was presented, with an outer diameter of 16° , an inner diameter of 12° , and a central active radius of 4.5° . The color ring rotated randomly during each trial. The placeholders in the recall phase corresponded to the positions of the colored squares in the previous memory array, with the placeholder for the remembered square being bolded. Participants were required to use the mouse to select the target color on the ring, with no time limit for their response until they made a choice.

The experiment began with a 1000 ms fixation point, followed by a 300 ms memory array. In all trials, the memory array presented two black rectangular lines, each positioned at least 2.5° from the fixation point on either side. Each memory item was a solid black rectangular line (RGB: 0, 0, 0) with a visual angle of $2.2^\circ \times 0.5^\circ$. The luminance of the black lines was 1 cd/m^2 . The orientation of these memory items was randomly selected from 10° to 170° , with a minimum separation of 10° between any two items. This was followed by a 900 ms retention interval, during which the fixation point remained at the center of the screen. Finally, the recall interface appeared with a double-ring circle randomly placed at the same position as the previously presented memory items. The outer diameter of the double-ring circle was 3.5° , the inner diameter was 2.2° , and the gap between the rings contained two hollow circles (visual angle: $1.3^\circ \times 1.3^\circ$) presented diagonally and movable via the mouse. The double-ring circle underwent random rotation during each trial. Participants were required to adjust the orientation of the double-ring circle to match the orientation of the corresponding line in the original memory array. They could rotate the hollow circles using the mouse, and after fitting them to the determined orientation, they clicked the right mouse button to record their response, with no time limit.

3.1.5 Transcranial Alternating Current Stimulation (tACS)

Electrode placement followed the same procedure as in Experiment 1. In the true stimulation condition, the current frequency was set at 4 Hz, and stimulation started at the maximum current intensity of $1500 \mu\text{A}$ (peak-to-peak amplitude). If participants experienced photic visual illusions or other sensations like tingling during the $1500 \mu\text{A}$ stimulation, the current intensity was reduced in increments of $50 \mu\text{A}$ until no photic illusions or other discomforts were felt. If no such sensations occurred at $1500 \mu\text{A}$, this intensity was used. In the sham stimulation condition, the electrode placement was identical to the true stimulation condition, but the electrical stimulation was only applied at the start and end of the session for 30 seconds each, to provide participants with a mild tingling sensation similar to continuous stimulation, making it difficult for them to distinguish the type of stimulation they received. The average stimulation intensity for all participants was $1341.07 \pm 200.49 \mu\text{A}$. Before starting the stimulation, participants were shown task instructions and briefed on the experimental task. Once they understood the task, they completed the practice trials, followed by feedback on their performance. After confirming that they understood the task, the tACS device was activated, and

they proceeded to complete the subsequent task. The total duration of tACS stimulation was 37 minutes. The experiment followed a single-blind design, with the order of true and sham stimulation balanced between participants, and the interval between the two experimental sessions was more than one week.

3.1.6 Data Analysis

The data analysis for Experiment 2 was the same as in Experiment 1. The Bayesian Information Criterion (BIC) comparison between the SwapModel and the VariablePrecisionModel showed an average ΔBIC of -0.71 under true stimulation and -1.38 under sham stimulation, with 31 participants supporting the SwapModel. Subsequently, the StandardMixtureModel was compared with the SwapModel, showing an average ΔBIC of -2.08 under true stimulation and -0.68 under sham stimulation, with 42 participants supporting the StandardMixtureModel. Therefore, the StandardMixtureModel was used for data fitting in this experiment. In the entire dataset, the distribution of systematic errors under each condition was within the preset reasonable range, so these errors were not further modeled as significant confounding factors in the statistical analysis. Paired sample t-tests were conducted for the G -values and SD -values under the 4 Hz and sham stimulation conditions based on the metrics derived from the StandardMixtureModel.

3.2 Experimental Results

We combined the results from the two sequence conditions. Regardless of whether participants completed the color or orientation task first, the first task was categorized as the “first task,” and the second task was categorized as the “second task.” Pearson correlation analyses were conducted between individual stimulation current intensities and the G -values and SD -values under different conditions. The results indicated that for the first task, stimulation current intensity was not significantly correlated with the G -values under true stimulation ($r(55) = -0.17$, $p = 0.191$) or SD -values ($r(55) = -0.01$, $p = 0.929$), nor with the G -values ($r(55) = -0.15$, $p = 0.263$) or SD -values ($r(55) = 0.10$, $p = 0.436$) under sham stimulation. For the second task, stimulation current intensity was also not significantly correlated with the G -values under true stimulation ($r(55) = 0.26$, $p = 0.053$) or SD -values ($r(55) = 0.06$, $p = 0.664$), nor with the G -values ($r(55) = 0.23$, $p = 0.083$) or SD -values ($r(55) = 0.03$, $p = 0.811$) under sham stimulation. This suggests that individual differences in the electrical stimulation received did not influence the experimental outcomes.

For the SD -values of the first task, paired sample t-tests were conducted (as shown in Figure 5). The results showed a significant difference between 4 Hz tACS and sham stimulation at the 0.05 significance level, $t(55) = -2.50$, $p = 0.015$, Cohen's $d = -0.33$. Further comparison of the mean values revealed that the SD -value under the 4 Hz tACS condition (20.66 ± 4.91) was smaller than the SD -value under the sham stimulation condition (22.03 ± 4.87). A higher SD -value indicates poorer working memory precision, thus suggesting that 4 Hz tACS significantly improved the precision of the first task. For the G -values of the first task, a paired sample t-test revealed no significant difference between the stimulation conditions, $t(55) = -0.39$, $p = 0.697$, indicating that 4 Hz tACS did not affect the number of items remembered in the first task.

For the SD -values of the second task, paired sample t-tests were conducted. The results showed no significant differences

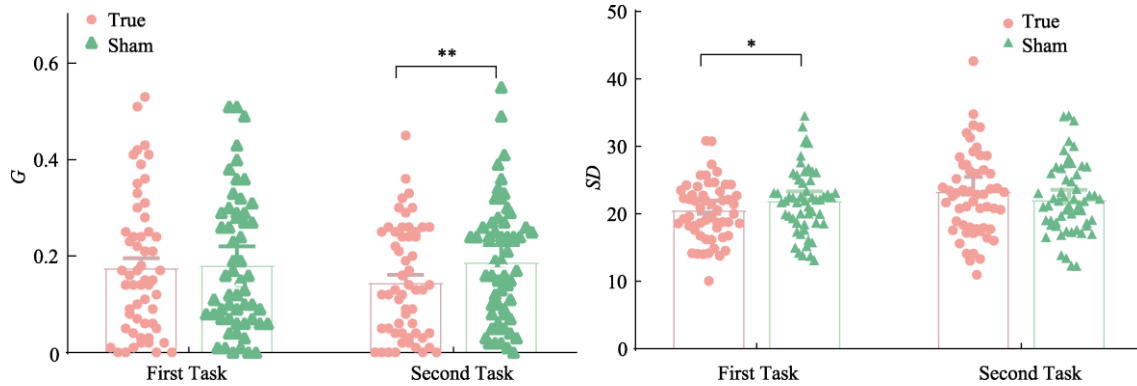


Figure 5. Guess rate G and accuracy SD results for the two tasks in Experiment 2. The first task refers to the task completed by the participant first, and the second task refers to the one completed second. Note: In both the first and second task plots, whether for G or SD , circles represent real stimulation conditions, and triangles represent sham stimulation conditions.

between the stimulation conditions and the task, $t(55) = 1.62$, $p = 0.111$, indicating that 4 Hz tACS did not affect the precision of the second task. For the G -values of the second task, paired sample t-tests showed significant differences between 4 Hz tACS and sham stimulation at the 0.05 significance level, $t(55) = -3.16$, $p = 0.003$, Cohen's $d = -0.42$. Further comparison of the means revealed that the G -value under the true stimulation condition (0.15 ± 0.11) was lower than that under the sham stimulation condition (0.19 ± 0.13). A lower G -value indicates more working memory items, suggesting that 4 Hz tACS significantly increased the number of items in the second task.

These findings confirm our research hypothesis. The results indicate that for the first task, under true stimulation, when participants completed the practice task before receiving electrical stimulation, their visual working memory precision significantly improved, with memory quantity remaining unchanged. This result is consistent with the findings from the post-stimulation group in Experiment 1, further demonstrating that electrical stimulation applied after the practice phase only improves memory precision without affecting memory quantity (supporting Hypothesis 2a). However, in the second task, due to the change in task context, the neural system must dynamically adjust the length of the theta cycle to accommodate the new encoding demands of the items, and individuals also re-establish a new memory strategy. Specifically, while memory precision remains unchanged, memory quantity significantly increases, a result that is consistent with the pre-stimulation group in Experiment 1 (supporting Hypothesis 2b).

4 General Discussion

This study aimed to investigate the impact of the timing of electrical stimulation on WM regulation and whether this regulatory effect would change in a new task context. When tACS is applied before the practice phase of a new task, it reduces theta frequency and increases gamma activity, enabling participants to increase the number of memory items while maintaining memory precision (as seen in the pre-stimulation group in Experiment 1 and the second task in Experiment 2). However, applying stimulation after practice yields different results: after brief practice, individuals form stable memory strategies. Even with low-frequency tACS, the memory quantity does not change, but memory precision is enhanced (as seen in the post-stimulation group in Experiment 1 and the first task in

Experiment 2).

Similar results have been observed in long-term memory studies, where the timing of stimulation affects tACS's efficacy. For example, applying stimulation before task performance improves word pair memory, while applying stimulation during the task (the exact timing of practice is not clarified in the study) has no effect (Paßmann et al., 2024). From a neural regulation perspective, applying tACS before the task reduces theta frequency in the brain, thereby increasing the cycle length and accommodating more gamma cycles, thus increasing the number of memory items. However, when stimulation is applied after the task, the theta frequency stabilizes, and the tACS stimulation enhances gamma amplitude, improving the phase-amplitude coupling between theta and gamma (Lega et al., 2016), thereby improving memory recall accuracy. This aligns with previous studies (Ruhnau et al., 2016), where tACS at the alpha frequency was found to specifically regulate visual cortex activity, with the effects depending on the brain's state (e.g., the eyes open condition being more sensitive). Under the eyes open condition, alpha oscillations in the visual cortex are weaker, making the brain more susceptible to external tACS, which leads to significant phase-locking. In contrast, under the eyes closed condition, alpha oscillations naturally increase ("alpha blocking" phenomenon), making the brain more resistant to external tACS interference. When the task context changes, the gamma waves representing the items in the first task (e.g., color) are no longer suitable for the new task (e.g., orientation). In the second task, the gamma cycle or amplitude may change, and the neural system must dynamically adjust the length of the theta cycle to meet the encoding requirements of the new items. Therefore, when the task context changes, individuals reassess their resource pool and develop a new resource allocation strategy based on the task's features.

From a psychological inertia perspective, during repeated practice, a strong association is formed between the context representation and the corresponding behavior representation. Once the context representation is activated, the related behavior representation is also triggered, leading to automated decision-making or behavior (Danner et al., 2008). Therefore, after multiple practice sessions, when participants enter the formal experiment with the same context setup as the practice phase, they automatically apply the resource allocation strategy used during practice. Based on the results, regardless of whether tACS stimulation is applied, the number of memory items is

unlikely to change. However, when participants perform the second task, they do not carry over the memory strategy used in the first task. This is because repeated behavior is more likely in stable environments, while behavior in unstable contexts is harder to repeat (Ouellette & Wood, 1998). In Experiment 2, when the task context of the second task changes, participants reallocate their memory resources according to the new task requirements and construct new memory strategies. This suggests that individuals possess cognitive flexibility, adjusting their memory strategies in response to changes in task context. They are able to reassess their resource state and optimize their memory strategies according to the task background, achieving the best cognitive performance.

This study used two dependent variables, with effect sizes ranging from 0.334 to 0.629, which fall within the medium range based on effect size classifications (Sawilowsky, 2009), indicating that the experimental manipulation was effective. A review found that individuals with schizophrenia perform significantly worse than healthy controls on working memory tasks, with an overall effect size of 0.452 (Lee & Park, 2005), which is similar to the effect sizes observed in this study. For the G-value, which represents the guess rate, an increase in this value may indicate the loss of memory representations or an excessive memory load. The SD-value represents the precision of memory representations (standard deviation), and an increase in this value may reflect increased neural noise or impaired binding ability (Schneegans & Bays, 2017). Changes in these parameters are not only important theoretically but also have potential clinical implications. For example, changes in the SD-value and G-value could serve as indicators for assessing the impact of neurodegenerative diseases or cognitive aging. Clinical research has shown that neurodegenerative diseases can affect SD-values. For example, Parkinson's patients show significantly lower working memory precision than healthy controls, but after about three months of dopaminergic treatment, their working memory precision significantly improves to healthy levels (Zokaei et al., 2015). Additionally, cognitive aging impacts both SD and G-values. Compared to younger individuals, older adults show higher guess rates and lower precision in visual working memory tasks (Peich et al., 2013), which is primarily due to weakened neural activity and inhibitory mechanisms, leading to instability in memory representations, causing target information to be lost (increased G-value) and less precise memory representations, with greater variability during recall (increased SD-value). Future research can further explore the potential of these parameters as diagnostic tools or as indicators for evaluating intervention effects.

Furthermore, transcranial alternating current stimulation (tACS) has broad potential applications. It can enhance cognitive functions such as attention, memory, and perception, and can also be used in the field of mental health to modulate emotions and alleviate symptoms of depression and anxiety. tACS may even be applied to treat neurological and psychiatric disorders (Tavakoli & Yun, 2017). Studies have shown that tACS, as a non-invasive brain stimulation technique, has potential therapeutic value in various diseases, including neurodegenerative diseases (e.g., Alzheimer's disease, Parkinson's disease), psychiatric disorders (e.g., schizophrenia, depression, insomnia), and chronic pain (Antal & Paulus, 2013; Elyamany et al., 2021; Zhang & Li, 2022). Schizophrenia patients often exhibit cognitive dysfunction, which severely affects their daily life

quality and functional recovery. A study administered theta-frequency tACS to schizophrenia patients while they performed an n-back task (a task used to assess working memory). The results showed that, after treatment, the patients' working memory, task processing speed, and attention significantly improved, and the effects persisted for 50 days (Sreeraj et al., 2019). The findings of this study are of great significance for the application of tACS. The timing of task performance and tACS stimulation plays a key role in the effectiveness of electrical stimulation. Therefore, when using tACS for therapeutic purposes, the timing of stimulation should be carefully considered to avoid missing the desired therapeutic effects due to improper stimulation timing.

Although this study successfully verified our experimental hypotheses, there are still some limitations that need to be pointed out. First, the two experiments differed slightly in methodology. In Experiment 1, the stimulation intensity was adjusted starting from 1500 μA , and if discomfort occurred, it was reduced to 1000 μA , whereas in Experiment 2, it was gradually decreased in 50 μA increments. This may have caused subtle differences between the two experiments. Additionally, Experiment 1 adopted the experimental design by Guo et al. (2021), where retroactive cues appeared before stimulus presentation, whereas Experiment 2 did not include these cues. As a result, the task difficulty in Experiment 1 was greater than that in Experiment 2. Furthermore, this study did not further verify whether individualized stimulation intensity induced equivalent electric fields. Future studies should use modeling tools such as SimNIBS or ROAST for individual head modeling simulations to more accurately control stimulation intensity and distribution, thus improving the comparability and interpretability of neural modulation. Secondly, in both experiments, participants received feedback on their deviation values during the practice phase, which allowed them to effectively monitor the validity of their resource allocation strategies. However, in the formal experimental phase, we did not provide corresponding feedback, which led participants to rely on the memory strategies formed during the practice phase to allocate resources. In the practice phase of the second task in Experiment 2, participants were able to adjust their strategies based on the feedback provided, forming new task schemas. Therefore, this experiment may have introduced the additional variable of "feedback," and future research should strictly control this variable to more accurately verify the conclusions of this study. Finally, in the post-stimulation condition of Experiment 1 and the first task phase of Experiment 2, participants persisted in using the memory strategies formed during practice, which might be because they did not realize that tACS stimulation could enhance their memory resources. If we explicitly informed participants about the increase in resources during the instructions phase, would they modify their task schemas and reallocate resources in the formal phase? This question warrants further investigation in future research.

5 Conclusion

The experimental results revealed that applying tACS stimulation before the task practice increases the number of items in working memory (WM), while applying tACS after practice enhances memory precision. However, this regulatory effect is not fixed; when encountering a new task, individuals reconstruct their memory strategies, thereby maximizing the utilization

tion of the enhanced resources.

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