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Investigating the Effects of Repetitive Transcranial Magnetic Stimulation of the Dorsolateral Prefrontal Cortex on Response Inhibition and Cognitive Flexibility in Patients with Generalized Anxiety Disorder

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Abstract

Background: Generalized anxiety disorder (GAD) is characterized by excessive, uncontrollable, and persistent worry about various life events. Evidence suggests that deficits in response inhibition and reduced cognitive flexibility contribute to the persistence of this disorder.

Objective: The present study aimed to investigate the effects of repetitive transcranial magnetic stimulation (rTMS) of the dorsolateral prefrontal cortex on response inhibition and cognitive flexibility in individuals with GAD

Method: This quasi-experimental study employed a pre-test–post-test design with a control group. The study population comprised FARAJA police officers referred to the neurology and psychiatry department of Imam Sajjad Hospital in Tehran over a nine-month period. Thirty participants were selected through convenience sampling and randomly assigned to experimental and control groups (n = 15 per group). Response inhibition was assessed using the Stroop Color–Word Test, and cognitive flexibility was assessed using the Cognitive Flexibility Inventory developed by Dennis and Vander Wal. The experimental group received 20 sessions of low-frequency (1 Hz) rTMS over the right dorsolateral prefrontal cortex at 110% of the motor threshold. Each session lasted 30 minutes, and sessions were conducted five times per week over one month.

Results: The experimental group demonstrated significantly greater improvements in response inhibition measures compared with the control group ($p \leq 0.001$). Cognitive flexibility also increased significantly in the experimental group relative to the control group ($p \leq 0.001$).

Conclusion: Repetitive transcranial magnetic stimulation of the dorsolateral prefrontal cortex was associated with improvements in response inhibition and cognitive flexibility in individuals with GAD. These findings suggest that rTMS may represent a potential non-invasive intervention for improving specific cognitive functions in this population. However, as anxiety symptoms were not directly assessed as outcome measures in the present analysis, the extent to which these cognitive changes relate to clinical symptom improvement remains unclear.

Trial Registration: Iranian Registry of Clinical Trials (IRCT), registration number IRCT20250129064556N1.

Keywords: Repetitive transcranial magnetic stimulation (rTMS); response inhibition; cognitive flexibility; generalized anxiety disorder (GAD).

1. Introduction

Generalized anxiety disorder (GAD) is a mental and behavioural disorder characterized by excessive, uncontrollable, and often irrational worry about events or activities, which frequently interferes with daily functioning (1). Individuals with GAD may worry excessively about ordinary matters, such as health, finances, death, family, relationships, or work-related difficulties (2). Symptoms can include excessive worry, restlessness, sleep disturbance, fatigue, irritability, sweating, and trembling (1).

The neurobiological foundations of GAD have been extensively investigated (3). Dyscoordination among different brain regions has been proposed as a principal neurobiological feature, particularly reduced resting-state functional connectivity between

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the amygdala and the prefrontal cortex in both adults and adolescents with the disorder (4, 5). Structural and functional neuroimaging studies have also identified differences between individuals with GAD and healthy controls, not only in frontolimbic regions but also in the anterior cingulate cortex, a downstream projection target of the amygdala (6). Reduced amygdala–prefrontal connectivity during adolescence and adulthood has been consistently associated with GAD (5). The prefrontal cortex, especially its ventral regions, is essential for effective emotion regulation and appears to exert control over negative emotions such as anxiety (7). Ventromedial prefrontal cortical activity has been shown to increase following pharmacological and psychological interventions in individuals with GAD. Furthermore, frontolimbic structures not only influence anxiety-related responses but also appear to regulate autonomic mechanisms differently in affected individuals (8).

At the neural level, the disturbed interaction between emotional and cognitive information in GAD may be explained by abnormal interactions between the ventromedial and dorsolateral prefrontal cortices (9). The dorsolateral prefrontal cortex (DLPFC) contributes to the maintenance and regulation of top-down control over the ventral prefrontal cortex and related subcortical regions to guide appropriate behaviour (10, 11). On this basis, altered or excessive DLPFC activity has been strongly associated with anxiety disorders (12).

Individuals with GAD experience difficulties across several domains of emotional and cognitive processing, including cognitive biases that may contribute to the maintenance and severity of anxiety symptoms (13). Hyperactivity or altered functioning of the ventromedial and dorsolateral prefrontal cortices has been implicated in these cognitive and emotional processes (13). Key executive functions associated with the DLPFC include working memory, cognitive flexibility, planning, inhibition, and abstract reasoning (14). Nevertheless, the DLPFC is not solely responsible for executive functioning; complex mental activity depends on interactions among multiple cortical and subcortical circuits. Therefore, cognitive difficulties observed in GAD should be considered as one component of a broader and multidimensional clinical presentation rather than as a single or primary determinant of the disorder.

Cognitive flexibility is an intrinsic property of the cognitive system and is commonly understood as the mental capacity to regulate activity and content, switch between different task rules and behavioural responses, maintain multiple concepts simultaneously, and shift internal attention between them. Traditionally regarded as an executive function, cognitive flexibility is a critical component of adaptive and flexible behaviour. More broadly, it can also refer to a set of brain characteristics that facilitate flexible yet contextually relevant transitions between functional brain states (15).

Human functional magnetic resonance imaging studies and animal optogenetic research indicate that cognitive flexibility depends on coordinated activity across several brain regions, including the prefrontal cortex, anterior cingulate cortex, posterior parietal cortex, basal ganglia, and thalamus (16–18). Individuals with GAD have been reported to experience difficulties in both response inhibition and cognitive flexibility. Research suggests that, during an emotional Stroop task, individuals with GAD may show greater difficulty in conflict monitoring when naming the colour of threat-related words than non-anxious individuals, although these findings have been criticized because many studies did not adequately control for

important lexical characteristics (19). These findings suggest that alterations in cognitive flexibility may be associated with anxiety-related cognitive processing, but they do not imply that such alterations are specific to GAD or solely responsible for the persistence of the disorder.

Inhibitory control, also termed response inhibition, is a cognitive process, and specifically an executive function, that enables an individual to suppress impulses and dominant or habitual behavioural responses to stimuli in order to select a more appropriate behaviour consistent with goal attainment (20, 21). Self-control is an important aspect of inhibitory control (22). Impaired response inhibition has been reported in individuals with GAD (23). However, findings from related anxiety disorders should be interpreted cautiously when considering GAD. For example, Fujii et al. (24) examined individuals with generalized social anxiety disorder rather than GAD and used the Wisconsin Card Sorting Test (WCST) to assess executive functioning. They reported an association between anxiety severity and perseverative errors on the WCST. Because the WCST primarily assesses executive processes such as set-shifting and cognitive flexibility rather than response inhibition specifically, these findings provide indirect evidence of a relationship between anxiety severity and executive dysfunction rather than direct evidence of response inhibition deficits in GAD. Accordingly, the results of Fujii et al. (24) are relevant to the broader relationship between anxiety and executive functioning but should not be considered direct evidence of impaired response inhibition in GAD.

Repetitive transcranial magnetic stimulation has also been associated with improvements in cognitive functioning. Several studies have examined its cognitive effects in Alzheimer's disease, post-traumatic stress disorder, and major depressive disorder, while meta-analyses have evaluated its effects on symptoms of anxiety disorders, including GAD. Despite the established association of GAD with response inhibition and cognitive flexibility, considerably less attention has been directed toward whether these cognitive functions can be modified through rTMS in patients with GAD. Therefore, investigating these functions may provide additional insight into the cognitive effects of rTMS in this population, without assuming that cognitive changes alone account for the clinical manifestations of GAD.

Current treatments for GAD primarily include psychological interventions, particularly cognitive-behavioural therapy (CBT), and pharmacological treatments such as selective serotonin reuptake inhibitors and serotonin–noradrenaline reuptake inhibitors. CBT directly targets maladaptive cognitive and behavioural processes, including excessive worry, threat-related interpretations, avoidance, and emotion regulation difficulties, and has demonstrated efficacy in reducing anxiety symptoms. Pharmacological treatments can also reduce the severity of anxiety symptoms and may indirectly improve cognitive and emotional functioning. However, treatment response is variable, and some individuals experience residual symptoms or tolerability difficulties, highlighting the need for complementary or alternative therapeutic approaches.

In this context, rTMS is a non-invasive neuromodulation technique that may influence the activity of specific cortical regions and their associated functional networks. Unlike CBT, which primarily modifies maladaptive cognitive and behavioural patterns through structured psychological techniques, and unlike pharmacological interventions, which exert broader neurochemical effects, rTMS can be applied to a targeted cortical region with the potential to modulate neural circuits

implicated in both cognitive control and anxiety regulation. Evidence that rTMS may affect executive functions, including response inhibition and cognitive flexibility, provides a rationale for examining whether its therapeutic effects in GAD extend beyond reductions in subjective anxiety symptoms. Nevertheless, rTMS should not be considered a replacement for established treatments; rather, its potential value lies in providing an additional therapeutic option, particularly for individuals who show inadequate response, residual symptoms, or limitations with existing interventions.

Police work is widely recognized as highly stressful and involves repeated exposure to potentially psychologically traumatic events, sometimes described as critical incidents. As public-safety personnel, police officers report high rates of symptoms consistent with a range of mental disorders, including post-traumatic stress disorder, panic disorder, social anxiety disorder, major depressive disorder, and GAD (26). Despite the considerable burden of anxiety and other psychological symptoms among police personnel, rTMS—an increasingly used non-pharmacological intervention for psychiatric disorders—has received limited research attention in this occupational group. The occupational context of police personnel therefore provides a clinically relevant population in which to investigate the potential effects of rTMS on anxiety-related and cognitive outcomes. However, the present study does not assume that police personnel with GAD respond differently to rTMS than individuals with GAD in the general population; rather, the study specifically focuses on police personnel with GAD, and its findings should therefore be interpreted within this occupationally defined population.

Although evidence supporting the efficacy of rTMS for GAD has grown, Cui et al. (27) characterized its effects as moderate, while Griffiths et al. (28) concluded that further systematic research is required to establish the efficacy of rTMS for the treatment of GAD. Accordingly, the present study was designed to examine whether low-frequency rTMS of the DLPFC could improve response inhibition and cognitive flexibility and whether such changes were accompanied by reductions in anxiety symptoms among police personnel with GAD. By examining both cognitive and clinical outcomes, this study seeks to investigate the potential effects of rTMS on specific executive functions alongside anxiety symptoms in this occupationally defined population. The findings are intended to provide evidence regarding the potential utility of rTMS for police personnel with GAD and should not be interpreted as directly generalizable to all individuals with GAD.

2. Research Method

The present study was a randomized controlled trial with a pre-test–post-test design and a control condition. The study population comprised male police personnel, as female police officers are generally underrepresented in operational units such as special units, relief units, and road police. Participants were recruited from police personnel who presented with symptoms of GAD for treatment at Imam Sajjad Hospital of FARAJA in Tehran over a nine-month period, from the beginning of February 2024 to the end of November 2024. The trial was registered retrospectively with the Iranian Registry of Clinical Trials (IRCT: 20250129064556N1).

Following initial screening, participants underwent a Structured Clinical Interview for DSM-5 (SCID-5-CV) conducted by a psychiatrist. Eligibility was determined according to DSM-5 diagnostic criteria. The Generalized Anxiety Disorder-7 (GAD-7) was used to assess the severity of anxiety symptoms (29), but it was not used as the sole basis for diagnosis. Among eligible

individuals, 30 participants who met the inclusion criteria and received a confirmed diagnosis of GAD were recruited through convenience sampling and randomly allocated to the experimental group (n = 15) or control group (n = 15). An additional five participants per group were planned to account for potential attrition.

2.1. Participants

Inclusion criteria were: male sex; employment as police personnel; provision of informed consent; a history of GAD for at least six months; absence of comorbid neurological or psychiatric disorders; absence of substance misuse; and no receipt of similar therapeutic interventions during the preceding six months. Participants were excluded if they withdrew consent or were absent from more than two intervention sessions.

The study population was restricted to male police personnel because of the limited representation of female personnel in the operational units from which participants were recruited. This sampling characteristic limits the generalizability of the findings to female police personnel and to non-police populations with GAD.

2.2. Research Instruments

2.2.1. Repetitive Transcranial Magnetic Stimulation

Repetitive transcranial magnetic stimulation (rTMS) is a non-invasive neuromodulation technique that uses repeated magnetic pulses to modulate cortical excitability. Its effects depend on several stimulation parameters, including frequency, intensity, duration, stimulation target, and number of treatment sessions. In the present study, low-frequency rTMS was administered at 1 Hz and 110% of each participant's motor threshold to the right dorsolateral prefrontal cortex (right DLPFC). The right DLPFC was targeted using the international 10–20 EEG system, with the F4 position used to approximate the stimulation site. Each session lasted 30 minutes, with five sessions per week for four consecutive weeks, totaling 20 sessions.

2.2.2. Generalized Anxiety Disorder-7 (GAD-7)

The GAD-7, developed by Spitzer et al. (29), consists of seven items assessing the severity of generalized anxiety symptoms during the preceding two weeks, plus one additional item assessing the extent to which symptoms interfere with daily functioning. The seven principal items are scored from 0 to 3, yielding a total score ranging from 0 to 21, with higher scores indicating greater anxiety severity. A score of 10 or higher is commonly used as a cut-off for clinically significant anxiety. Spitzer et al. (29) reported excellent internal consistency (Cronbach's $\alpha = 0.92$) and good two-week test–retest reliability ($r = 0.83$). Convergent validity was demonstrated through correlations with the Beck Anxiety Inventory and the anxiety subscale of the Symptom Checklist-90. The validity and reliability of the Persian version of the GAD-7 have also been reported in an Iranian sample by Naeinian et al. (30). In the present study, the GAD-7 was used to quantify anxiety symptom severity at pre-test and post-test, whereas the final diagnosis of GAD was established by a psychiatrist according to DSM-5 criteria.

2.2.3. Computerised Stroop Color–Word Test

The computerized Stroop Color–Word Test was used to assess response inhibition and selective attention. The task consisted of a practice phase followed by the main experimental phase. During the main phase, 96 colour-word stimuli were presented, including 48 congruent and 48 incongruent trials involving the colours red, blue, yellow, and green. Stimuli were presented sequentially in random order. Each stimulus was displayed for 2,000 milliseconds, followed by an inter-stimulus interval of 800

milliseconds. Participants were instructed to identify the ink colour of each word while ignoring its semantic meaning.

Reaction time and accuracy were recorded separately for congruent and incongruent trials. Mean reaction time (RT) was calculated for each condition. Interference time was calculated as:

Interference time = Mean RT for incongruent trials – Mean RT for congruent trials.

Thus, a larger positive interference time indicated a greater increase in response time under incongruent relative to congruent conditions. In addition, an interference score based on accuracy was calculated as:

Interference score = Number of correct responses in the congruent condition – Number of correct responses in the incongruent condition.

The interference time and interference score represent different aspects of Stroop interference: interference time reflects the additional response time associated with incongruent stimuli, whereas the interference score reflects the reduction in response accuracy under incongruent conditions. These indices were therefore not treated as interchangeable measures. Previous research has reported acceptable test–retest reliability for the Stroop task, with coefficients ranging from 0.80 to 0.91 (31).

2.2.4. Cognitive Flexibility Inventory (CFI)

The Cognitive Flexibility Inventory developed by Dennis and Vander Wal (32) consists of 20 items assessing cognitive flexibility. The inventory assesses the individual's ability to perceive alternative explanations and solutions, perceive situations as controllable, and generate alternative responses to difficult situations. Items are rated on a five-point Likert scale ranging from "completely disagree" to "completely agree." Items 2, 4, 7, 9, 11, and 17 are reverse-scored. Dennis and Vander Wal (32) reported convergent validity of 0.75 with the Martin and Rubin Cognitive Flexibility Scale and concurrent validity of –0.39 with the Beck Depression Inventory. Evidence for the reliability and validity of the Persian version has also been reported in Iranian samples, including test–retest reliability of 0.71 and Cronbach's alpha of 0.90 for the total scale (33).

2.2.5. Continuous Performance Test

The Continuous Performance Test (CPT) was used to assess sustained attention and inhibitory control. In the Persian version used in the present study, 150 visual stimuli were presented, including 30 target stimuli and 120 non-target stimuli. Participants were instructed to respond to target stimuli while withholding responses to non-target stimuli. Each stimulus was presented for 200 milliseconds, with a one-second interval between consecutive stimuli. The total task duration, including the practice phase, was approximately 200 seconds.

The primary indices included omission errors, commission errors, correct responses, and reaction time. An omission error occurred when a participant failed to respond to a target stimulus and was interpreted primarily as an indicator of reduced sustained attention. A commission error occurred when a participant responded to a non-target stimulus and was interpreted as an indicator of impaired response inhibition or impulse control. Previous research has reported acceptable validity and reliability for the Persian version of the CPT.

2.3. Procedure

The study was approved by the Biomedical Research Ethics Committee of the University of Tabriz. Before participation, all participants received information about the study procedures and provided informed consent.

Eligible participants were recruited through convenience sampling and then randomly allocated to the experimental or

control group. Both groups completed the baseline assessments one week before the intervention and the post-intervention assessments one week after completion of the twentieth session. The assessment battery included the GAD-7, computerized Stroop Color–Word Test, Cognitive Flexibility Inventory, and Continuous Performance Test.

Participants in the experimental group received 20 sessions of low-frequency rTMS over four consecutive weeks, with five sessions per week. Stimulation was delivered at 1 Hz and 110% of the individual motor threshold for 30 minutes per session. Before each treatment session, participants wore hearing protection and removed objects sensitive to magnetic fields, including mobile phones, wristwatches, jewellery, credit cards, hearing aids, and metal dentures.

A MagVenture rTMS system (MagVenture, Denmark) equipped with an air-cooled figure-of-eight coil was used. The right DLPFC was targeted according to the international 10–20 EEG system, using the F4 position to approximate the stimulation site. Individual motor threshold was determined before stimulation, and the stimulation intensity was subsequently set to 110% of the participant's motor threshold. The figure-of-eight coil was selected because of its focal stimulation characteristics.

The control group attended 20 sessions according to the same schedule as the experimental group. The duration of sessions, treatment environment, and interaction with the researcher were kept as similar as possible between groups. In the control condition, the coil was positioned vertically to prevent active magnetic stimulation from reaching the participant's head. Thus, the control condition was designed to reproduce the treatment setting and procedures while withholding active magnetic stimulation. Following completion of the post-intervention assessment, participants in the control group were offered 20 free sessions of active therapeutic intervention for ethical reasons.

During rTMS administration, participants were seated comfortably and wore a treatment cap. The stimulation target was identified using the international 10–20 system, after which the motor threshold was determined and the stimulation intensity was adjusted individually. The stimulation protocol was then initiated and continued for 30 minutes. All rTMS sessions were administered by the researcher.

2.4. Blinding

The study used a control condition in which the coil was positioned vertically to prevent active magnetic stimulation, rather than using a dedicated sham coil. No formal assessment was performed to determine whether participants could correctly identify their group assignment; therefore, the effectiveness of participant blinding could not be objectively verified. Similarly, no formal blinding procedure or assessment of outcome-assessor blinding was implemented. These factors were considered when interpreting the findings and represent methodological limitations of the study.

2.5. Sample Size and Randomization

Thirty participants were included in the final study sample, with 15 participants allocated to each group. Participants were recruited using convenience sampling and subsequently randomly allocated to the experimental and control groups. An additional five participants per group were planned to account for potential attrition.

The original sample-size rationale was based on the recommendation of Delavar for experimental studies, according to which approximately 15 participants per group may be considered an acceptable minimum for certain experimental designs. However, no formal a priori power analysis based on an expected effect size was conducted. Therefore, the sample size should be

considered a limitation, particularly with respect to statistical power and the precision of effect estimates.

3. Results

Table 1 presents the descriptive statistics (mean and standard deviation) for the study variables at pre-test and post-test in the experimental and control groups.

Table 1. Descriptive indices of the research variables at pre-test and post-test

Variable / Index	Group	Pre-test (Mean ± SD)	Post-test (Mean ± SD)
Response inhibition – Congruent error	Experimental	0.905 ± 0.054	0.426 ± 0.024
	Control	0.903 ± 0.053	0.904 ± 0.054
Response inhibition – Incongruent error	Experimental	1.11 ± 0.053	0.658 ± 0.055
	Control	1.10 ± 0.049	1.07 ± 0.045
Interference score	Experimental	1.01 ± 0.039	0.741 ± 0.035
	Control	0.996 ± 0.038	1.00 ± 0.036
Interference time (ms)	Experimental	460.70 ± 15.65	267.35 ± 10.97
	Control	459.85 ± 15.70	461.61 ± 15.15
CFI – Alternatives	Experimental	44.80 ± 1.77	52.00 ± 0.598
	Control	44.40 ± 1.76	44.70 ± 1.72
CFI – Control	Experimental	33.85 ± 0.855	40.55 ± 0.472
	Control	33.01 ± 0.856	33.85 ± 0.855
CFI – Behavioural alternatives	Experimental	7.05 ± 0.351	9.50 ± 0.246
	Control	7.10 ± 0.298	7.15 ± 0.301
Sustained attention – Omission error	Experimental	232.45 ± 15.65	173.85 ± 6.13
	Control	231.00 ± 16.63	232.70 ± 16.63
Sustained attention – Commission error	Experimental	272.45 ± 10.08	230.25 ± 9.53
	Control	269.75 ± 9.60	272.40 ± 10.01

Interference score and interference time are indicators of performance differences between incongruent and congruent conditions in the Stroop task. Interference time is expressed in milliseconds and represents the increase in reaction time under incongruent relative to congruent conditions. Congruent and incongruent errors represent the number of incorrect responses in each condition.

Before conducting the multivariate analysis of covariance (MANCOVA), the required assumptions were examined. Normality of the distributions was assessed using skewness and kurtosis indices. As shown in Table 2, the skewness and kurtosis values of the study variables were within the range of –2 to +2, indicating no substantial deviation from normality.

Homogeneity of variance–covariance matrices were assessed using Box's M test. The result was non-significant (Box's M = 0.670, F = 0.211, df1 = 45, df2 = 4743.802, p = 0.789), indicating that the assumption of equality of variance–covariance matrices were satisfied.

Homogeneity of variances for the individual dependent variables was examined using Levene's test. The results were non-significant for all study variables ($p > 0.05$), indicating that the assumption of homogeneity of variances was satisfied.

Because pre-test scores were available for all dependent measures, the corresponding pre-test scores were included as covariates to control for baseline differences between groups. MANCOVA was then conducted to examine the effect of rTMS on response inhibition, cognitive flexibility, and sustained attention.

The multivariate effect of group was statistically significant (Wilks' $\lambda = 0.027$, $F = 84.518$, $p = 0.001$), indicating that the combined pattern of post-test dependent

variables differed significantly between the experimental and control groups after controlling for pre-test scores. To examine the separate effects of rTMS on individual outcome measures, univariate ANCOVAs were subsequently conducted within the multivariate framework. The results are presented in Table 2.

Table 2. Between-group effects on study variables in the experimental and control groups.

Variable	Sum of squares	df	Mean square	F	Sig.	Partial eta squared (ηp^2)
Congruent error	8.688	1	2.192	29	0.001	0.756
Incongruent error	4.240	1	1.584	18	0.001	0.625
Interference score	0.798	1	0.798	7.323	0.001	0.717
Interference time	364760.297	1	364760.297	25.608	0.001	0.812
Alternatives	443.656	1	443.656	19.144	0.001	0.398
Control	552.899	1	552.899	106.915	0.001	0.787
Behavioural alternatives	49.827	1	49.827	16.348	0.001	0.660
Omission error	33754.565	1	33754.565	25.252	0.001	0.465
Commission error	19006.624	1	19006.624	55.598	0.001	0.657

Regards to the Table 2, congruent and incongruent errors represent the number of incorrect responses to congruent and incongruent stimuli, respectively, and were used as indicators of response inhibition. Interference score represents the performance difference between incongruent and congruent conditions, reflecting the degree of interference produced by incongruent stimuli. Interference time represents the reaction-time cost associated with cognitive interference, expressed in milliseconds. CFI alternatives, control, and behavioural alternatives indices represent the corresponding components of cognitive flexibility; higher scores indicate better performance. Omission and commission errors were included as performance-error measures of sustained attention.

The results in Table 2 showed statistically significant between-group differences in all response-inhibition indicators. Specifically, the experimental group demonstrated lower congruent error, incongruent error, interference score, and interference time at post-test compared with the control group ($p \leq 0.001$). The corresponding partial eta squared values indicated substantial effect sizes ($\eta p^2 = 0.625–0.812$).

The results also showed statistically significant between-group differences in all assessed components of cognitive flexibility. The experimental group demonstrated higher scores on alternatives, control, and behavioural alternatives at post-test compared with the control group ($p \leq 0.001$), with partial eta squared values of 0.398, 0.787, and 0.660, respectively.

Regarding sustained attention, statistically significant between-group differences were observed for both omission and commission errors ($p \leq 0.001$). The experimental group showed fewer omission and commission errors at post-test compared with the control group, with partial eta squared values of 0.465 and 0.657, respectively.

Overall, the findings indicate that, after accounting for baseline performance, the experimental group receiving rTMS showed significantly better post-test performance

across measures of response inhibition, cognitive flexibility, and sustained attention compared with the control group.

4. Discussion

The present study examined the effects of repetitive transcranial magnetic stimulation (rTMS) on response inhibition, cognitive flexibility, and sustained attention in male police personnel with generalized anxiety disorder (GAD). The findings showed statistically significant between-group differences in the post-test measures of all cognitive domains, with the experimental group demonstrating better performance than the control group. These findings suggest that rTMS was associated with improvements in several cognitive functions in the present sample. However, because clinical symptoms of anxiety and cognitive biases were not directly assessed as outcome measures, the findings should be interpreted primarily in terms of cognitive performance rather than clinical symptom reduction.

4.1. Response inhibition

The findings showed that rTMS was associated with significantly improved response inhibition in individuals with GAD, as reflected by reductions in congruent and incongruent errors, interference score, and interference time in the experimental group compared with the control group ($p \leq 0.001$). These findings are broadly consistent with previous reports by Fujii et al. (24), Heydarpour et al. (35), Rodrigues et al. (36), and Griffiths et al. (28), although these studies differed from the present investigation with respect to sample characteristics, stimulation protocols, and cognitive measures.

One possible explanation for the observed improvement is the involvement of prefrontal executive-control systems in response inhibition. Individuals with GAD may exhibit difficulties in emotional and cognitive processing, including impairments in inhibitory control (13, 23). Response inhibition is an executive process that enables individuals to suppress dominant or prepotent responses and select responses more consistent with current task demands and behavioural goals (20). Consequently, improvement in inhibitory performance following rTMS may reflect enhanced efficiency of executive-control processes rather than a direct reduction in anxiety symptoms.

The DLPFC is involved in several executive functions, including cognitive inhibition, working memory, planning, cognitive flexibility, and abstract reasoning (14). Previous research has also indicated that rTMS can influence cognitive functioning through stimulation of prefrontal regions (37). In GAD, abnormalities in the interaction between cognitive-control and emotion-processing systems have been proposed as part of the neural mechanisms underlying the disorder (9–13). Accordingly, stimulation of prefrontal networks may facilitate top-down cognitive control and improve the ability to suppress inappropriate or competing responses.

The present findings therefore provide behavioural evidence that rTMS may influence response-inhibition performance in individuals with GAD. Nevertheless, the present study did not directly measure neural activity or connectivity; therefore, the proposed prefrontal mechanism should be considered a possible explanation rather than a demonstrated mechanism of change.

Cognitive-control models of GAD further emphasize the importance of executive processes in the psychopathology of anxiety (38, 39). Cognitive control involves the ability to maintain goal-directed behaviour and includes related processes such as working memory, shifting, and cognitive inhibition (15, 40, 41). Among these, cognitive inhibition has received particular attention in theoretical models of anxiety (15). The

improvement observed in the present study may therefore indicate that rTMS influenced one component of cognitive control, namely inhibitory performance. However, this interpretation should remain limited to the behavioural measures assessed in the present study.

4.2. Cognitive flexibility

The findings also demonstrated a statistically significant improvement in cognitive flexibility in the experimental group compared with the control group ($p \leq 0.001$). This finding is consistent with previous observations reported by Lee and Orsillo (19), Rosa-Alcázar et al. (23), and Rodrigues et al. (36), although differences in samples, intervention procedures, and assessment methods should be considered when comparing these findings.

Cognitive flexibility refers to the ability to shift between task rules, behavioural responses, or mental representations and to adapt cognitive processing according to changing task demands (15, 16). It is considered an important component of executive functioning and involves coordinated activity across a distributed network including the prefrontal cortex, anterior cingulate cortex, posterior parietal cortex, basal ganglia, and thalamus (16, 18).

The improvement in cognitive flexibility observed in the present study may be related to the effects of rTMS on prefrontal executive-control networks. The DLPFC plays an important role in cognitive flexibility and other executive functions (14). Repeated stimulation may therefore facilitate the efficiency of these networks and improve the ability to shift between competing response requirements. This interpretation is consistent with previous evidence suggesting that rTMS can influence cognitive functioning (37).

GAD has also been associated with difficulties in cognitive control and cognitive flexibility (19). From this perspective, the improvement observed in the present study may reflect enhanced ability to adapt cognitive responses to changing task requirements. Importantly, however, the present study did not directly assess cognitive biases; therefore, the finding should not be interpreted as evidence that rTMS reduced cognitive biases.

Although cognitive inflexibility and cognitive biases have been proposed as relevant features of GAD, any relationship between the observed improvement in cognitive flexibility and a possible reduction in cognitive bias remains hypothetical in the present study. Future studies should directly assess attentional or interpretive biases alongside cognitive flexibility to determine whether improvements in flexibility are associated with changes in anxiety-related cognitive biases.

4.3. Sustained attention

The present study additionally showed statistically significant differences between the experimental and control groups in omission and commission errors, indicating improved performance on the sustained-attention measure following rTMS ($p \leq 0.001$). These findings are broadly consistent with previous evidence suggesting that prefrontal rTMS may influence attention and other executive functions (37), although much of the existing evidence has been obtained in populations other than GAD.

Sustained attention refers to the ability to maintain an appropriate level of attention and respond consistently over time. This ability depends on distributed frontoparietal and cingulo-opercular networks, including prefrontal regions (17). Previous studies have also suggested that attentional abnormalities are relevant to anxiety disorders and may contribute to the maintenance of anxiety-related processing patterns (30).

The observed reduction in omission and

commission errors may therefore indicate improved attentional control following rTMS. One possible explanation is that stimulation of prefrontal regions enhanced the efficiency of cognitive-control processes involved in maintaining task goals and monitoring responses. Previous research has reported beneficial cognitive effects of prefrontal rTMS across several psychiatric populations (37). However, because the present study did not directly measure neural activity or attentional bias, the underlying neural mechanism cannot be established from the current data. Taken together, the findings across response inhibition, cognitive flexibility, and sustained attention suggest that rTMS was associated with a broader improvement in cognitive performance rather than an isolated change in a single executive process. The observation that improvements occurred across several cognitive measures may be consistent with the involvement of partially overlapping prefrontal executive-control networks. Nevertheless, the present behavioural findings do not establish whether these cognitive changes mediate clinical improvement in GAD.

4.4. Limitations

Several limitations should be considered when interpreting the findings of the present study. First, the sample consisted exclusively of male police personnel. This population was selected according to the characteristics of the study setting and recruitment procedure; however, restricting the sample to male police personnel limits the generalizability of the findings to women, non-police populations, and individuals with different occupational and demographic characteristics.

Second, the sample size was relatively small. Although additional participants were recruited to reduce the potential impact of participant withdrawal, a formal prospective power analysis was not reported. Therefore, the statistical estimates, particularly the effect-size estimates, should be interpreted cautiously and replicated in larger samples.

Third, the effectiveness of the sham condition and the success of participant blinding should be considered when interpreting the findings. Active and sham rTMS can differ in scalp sensations and auditory experiences, potentially allowing participants to infer their treatment condition. As a formal assessment of treatment allocation was not performed, the degree to which participant expectations may have influenced the observed effects cannot be established. Future studies should include a systematic blinding assessment in which participants are asked to indicate their perceived treatment allocation after the intervention. Similarly, blinding of outcome assessors should be explicitly reported and maintained whenever possible.

Fourth, the study did not directly assess anxiety symptom severity as a primary outcome of the intervention. Although the GAD-7 was used during participant assessment/screening, the present analyses focused on cognitive performance measures. Consequently, the observed improvements cannot be interpreted as direct evidence that rTMS reduced the clinical symptoms of GAD.

Fifth, cognitive biases were not directly measured. Therefore, the possibility that improved cognitive flexibility resulted in reduced anxiety-related cognitive biases remains a theoretical interpretation rather than an empirical finding of the present study.

Finally, the interpretation of the findings is limited to the specific rTMS protocol and cognitive measures used in this study. Different stimulation parameters, treatment durations, target regions, and cognitive tasks may produce different effects. Future research should therefore replicate these findings using larger and more diverse samples, formal power calculations, rigorous

sham and blinding procedures, direct measures of anxiety symptoms and cognitive biases, and longer-term follow-up assessments.

5. Conclusion

The present study found that repetitive transcranial magnetic stimulation (rTMS) was associated with significant improvements in response inhibition, cognitive flexibility, and sustained attention in male police personnel with GAD compared with the control condition. These findings provide behavioural evidence that rTMS may influence several aspects of cognitive functioning in this population.

The observed improvements in response inhibition, cognitive flexibility, and sustained attention are consistent with the proposed involvement of prefrontal executive-control systems in these cognitive processes. However, because the present study did not directly assess neural mechanisms, anxiety symptom reduction, or cognitive biases, the findings do not establish that rTMS reduces anxiety symptoms or cognitive biases through improved executive functioning.

Future studies with larger and more diverse samples, adequately powered designs, rigorous sham and blinding assessments, and direct measurement of clinical symptoms and cognitive biases are needed to determine whether the cognitive improvements observed following rTMS translate into meaningful clinical benefits for individuals with GAD.

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Data Availability: All data generated or analysed during this study are included in this published article.

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