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Gamma Rhythms and Cognitive Function: A Study Based on 40-Hz Binaural-Beat Stimulation and the Stroop Task

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Abstract: *Alzheimer's disease (AD) is a progressive neurodegenerative disorder of the central nervous system that primarily affects older adults and is characterized by cognitive decline and behavioral disturbances. Currently, AD ranks as the fifth leading cause of death worldwide which has got World Health Organization (WHO)'s attention. Disruptions in gamma-band neural oscillations have been identified as a potential mechanism underlying cognitive impairment in AD. Hence gamma rhythm stimulation has become a novel therapeutic intervention. This approach has been shown to enhance cognitive function in individuals with AD and, in some cases, to facilitate cognitive improvement in healthy adults. The present study investigated the effects of 40 Hz binaural-beat auditory stimulation on cognitive inhibitory control, as well as the moderating roles of age and stimulus modality. Fifty-three healthy participants were recruited and assigned to one of three groups: 40 Hz auditory stimulation, normal auditory stimulation, or a no-sound control condition. Participants completed a Stroop task, and the behavioral performance, including accuracy and reaction time, served as the dependent variables. Results indicated no significant differences in accuracy among different age groups. However, reaction time exhibited a clear age gradient: younger adults responded fastest, older adults slowest, and middle-aged adults in between. Furthermore, accuracy in both auditory stimulation groups was lower than in the control condition, suggesting a potential inhibitory effect of 40 Hz auditory input on task performance. The potential reason is discussed. These findings support the processing speed theory and extend the interference failure–noise hypothesis by highlighting the role of gamma-frequency auditory stimulation in modulating cognitive performance. Moreover, the results offer insights for the development of cognitive enhancement strategies and potential interventions for the prevention and treatment of Alzheimer's disease. The study highlights the importance of considering age as a critical moderating factor in cognitive training.*

Keywords: *40 Hz binaural beat; Gamma rhythm; Cognitive inhibition; Stroop task; Age*

1. Introduction

Alzheimer's disease (AD) is a progressively worsening neurodegenerative disorder. Its primary clinical manifestations include cognitive decline, psychiatric and behavioral disturbances, and impaired social functioning[1]. AD is not a normal aspect of aging but a distinct pathological condition. The global prevalence of AD poses a significant public health challenge. According to the World Health Organization, one new case of dementia occurs every three seconds worldwide[2]. In the United States, approximately 6.7 million individuals currently live with AD, and this number is projected to double to 14 million by 2060[3]. Similarly, the situation in China is alarming. more than 10 million AD patients and an estimated 40 million individuals are experiencing mild cognitive impairment[4]. Current therapeutic approaches for AD primarily involve pharmacological treatments such as cholinesterase inhibitors and NMDA receptor antagonists[5][6]. However, these medications can only alleviate symptoms and do not halt disease progression. Recent developments in the study of gamma rhythms have created new opportunities for potential therapeutic interventions in AD.

Gamma rhythms are high-frequency neural oscillations, typically ranging from 30 to 100 Hz. 40 Hz is the most widely studied and functionally significant frequency. These oscillations are primarily generated by inhibitory interneurons in the cerebral cortex. Historically, abnormalities in gamma rhythms were regarded as passive byproducts of neuronal loss and pathological protein accumulation. However, pioneering research led by Li-Huei Tsai's group at the Massachusetts Institute of Technology challenged this view. Their studies demonstrated that artificially inducing aberrant gamma rhythms could elicit AD-like pathology and cognitive deficits, whereas restoring normal gamma rhythms could reverse these pathological changes and improve cognition[7]. This evidence suggests that gamma rhythm disruptions may play a causal role in AD pathogenesis rather than being merely a consequence. Furthermore, a 2019 study published in Cell showed that non-invasive 40 Hz light and sound stimulation in AD model mice produced robust, widespread therapeutic effects, confirming the feasibility of non-invasive interventions[8]. Building on this foundation, Cognito Therapeutics developed an audiovisual stimulation device that, in Phase II clinical trials, resulted in an 83% reduction in the rate of cognitive decline and a 61% reduction in brain atrophy among patients with mild to moderate AD following one hour of daily treatment[9].

Beyond its therapeutic potential in AD, gamma rhythm stimulation has also demonstrated cognitive benefits in healthy populations. Studies have shown that 40 Hz transcranial alternating current stimulation significantly enhances performance on N-back working memory tasks in healthy individuals[10]. Similarly, 40 Hz electrical stimulation has been associated with a 0.28 standard deviation improvement in abstract reasoning scores[11]. These findings suggest that gamma rhythm stimulation may represent a promising and safe approach for cognitive enhancement in healthy individuals. Previous research has primarily utilized transcranial alternating current stimulation or photic stimulation, both of which require specialized equipment and technical expertise. It limits their applicability for everyday use. Moreover, existing studies have predominantly focused on memory and attention. Limited attention has been paied to cognitive inhibition. To address these gaps, the present study employs 40 Hz binaural beat music as a form of gamma rhythm stimulation and utilizes the Stroop paradigm to assess cognitive inhibition. Participants' performance is evaluated based on their accuracy and reaction time. This research aims to improve the understanding of gamma rhythm effects on cognitive inhibition and to explore the feasibility of accessible, non-invasive cognitive enhancement methods.

2. Method

2.1 Participants

A total of 53 participants (M_{age} = 38.38, SD_{age} = 17.30) were randomly recruited for the study. Among them, 22 participants (M_{age} = 43.45, SD_{age} = 21.16) were recruited from Vancouver and Nanaimo, Canada, including 7 males and 15 females. The remaining 31 participants (M_{age} = 34.77, SD_{age} = 12.76) were recruited from Shanghai, China, comprising 15 males and 16 females. All participants were randomly assigned to one of three experimental groups - Group A, Group B, or Group C—each exposed to different experimental stimuli. In addition, participants were categorized into three age groups: individuals under 30 years old were assigned to the Young Group, those aged between 30–50 to the Middle-aged Group, and those over 50 to the Elderly Group. Participants were instructed to respond to a series of questions presented on a computer screen. Accuracy rates and reaction times were recorded using the PsychoPy software.

2.2 Stimuli

Two audio clips, created using Audacity software, were presented as musical stimuli to participants in Groups A and B. Group A received light music composed of natural sound effects sourced from Audacity's free sound library. Group B received the same musical material overlaid with a 40-Hz binaural beat, in which the left ear was presented with a 200-Hz waveform and the right ear with a 240-Hz waveform. These two waveforms were subsequently combined with the natural sound effects to produce the audio clips for Group B.

The reaction time task was programmed using PsychoPy software and consisted of four sections, each containing 10 questions. All questions employed variations of the Stroop test. In Section 1, participants viewed color words whose font color contradicted the semantic meaning of the word. They were instructed to ignore the word's meaning and select the correct font color. In Section 2, participants saw words indicating spatial positions (e.g., "up," "down," "left," "right") displayed in locations that contradicted their meaning. They were required to ignore the semantic content and select the correct screen position. In Section 3, participants were shown a series of identical numerical digits (ranging from 1 to 5, up to five digits per item) and were asked to report the quantity rather than the digit itself. In Section 4, participants were presented with images of clocks and asked to identify the time displayed.

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2.3 Design and Procedure

The study employed a between-subjects design. Participants were randomly assigned to one of the three groups. Initially, participants were asked to read and sign the consent form. They were then seated in front of a laptop and provided with noise-reducing headphones. Before the formal experiment began, participants in Groups A and B were exposed to their respective musical stimuli in advance to ensure auditory entrainment. The reaction time task commenced while the music was playing. Groups A and B completed the entire experiment with continuous background music, whereas Group C received no musical stimulation throughout the session.

During the formal experiment, all participants completed four sections comprising a total of 40 questions. At the beginning of each section, an instruction page introduced the task type and presented an example question, which was not included in data analysis. Subsequently, the four sets of experimental questions were displayed on the screen. The order of trials randomized within each section. Participants responded by pressing designated keys to submit their answers. The PsychoPy software automatically recorded both response accuracy and reaction time for each trial. Upon completing all four sections, participants concluded the experiment and received a gift for appreciation. The entire procedure lasted approximately five to ten minutes per participant.

2.4 Data Analysis

The raw data were first cleaned to remove invalid entries, specifically those containing incorrect responses or excessively long reaction time. In the first three sections, responses exceeding 5 seconds (> 3SD),per trial were considered invalid, while in the fourth section, responses exceeding 6 seconds (> 3SD),were excluded. After data cleaning, each participant's accuracy rate (C) and mean reaction time (RT) were computed.

To examine differences in performance among Group A, B, and C, one-way ANOVA analyses were conducted separately for accuracy and reaction time. Between-group t-tests were then performed to identify significant differences between specific groups. Similarly, to compare performance across age categories (Young, Middle-aged, and Elderly), one-way ANOVA analyses were conducted on accuracy and reaction time, followed by between-group t-tests to determine pairwise differences.

3. Results

3.1 One-way ANOVA analysis of Group A, Group B, and Group C

The results of the one-way ANOVA test are presented in Table 1. There was no significant difference in accuracy (C) among Group A ($M = 9.26, SD = 0.93$), Group B ($M = 9.24, SD = 0.82$), and Group C ($M = 9.72, SD = 0.31$, $p = 0.36$, $p > 0.05$). Similarly, analysis of reaction time (RT) revealed no significant difference among Group A ($M = 2.23, SD = 0.54$), Group B ($M = 2.18, SD = 0.50$), and Group C ($M = 2.09, SD = 0.49$, $p = 0.76, p > 0.05$).

3.2 T-test analysis for Group A, Group B and Group C

As shown in Table 1, the independent-sample t-test revealed a significant difference *($p=0.02$),* in accuracy (C) between Group A ($M = 9.26, SD = 0.93$) and Group B ($M=9.24, SD=0.82$). However, no significant difference ($p>0.05$) in reaction time (RT) was found between the two groups (*Group A:* $M =2.23, SD=0.54$; *Group B:* $M =2.18, SD =0.50$).

Similarly, there was no significant difference ($p>0.05$) in accuracy between Group A ($M=9.26, SD=0.93$) and Group C ($M = 9.72, SD = 0.31$). Reaction time also did not differ significantly ($p>0.05$) between Group A ($M=2.23, SD=0.54$) and Group C ($M=2.09, SD=0.49$).

In contrast, participants in Group B ($M =9.24, SD=0.82$) demonstrated significantly lower ($P=0.01$) accuracy than those in Group C ($M=9.72, SD=0.31$). However, no significant difference ($p>0.05$) in reaction time was observed between these groups (*Group B:* $M=2.18, SD=0.50$; *Group C:* $M=2.09, SD=0.49$).

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3.3 One-way ANOVA analysis of Young, Middle-aged, and Elderly

The results of one-way ANOVA analyses are presented in Table 2. There was no significant difference ($p>0.05$) in accuracy (C) among the Young ($M=9.28$, $SD=0.78$), Middle-aged ($M=9.25$, $SD=1.17$), and Elderly ($M=8.91$, $SD=1.22$) groups. In contrast, a significant difference ($p=0.004$) in reaction time (RT) was observed among the three age groups (*Young:* $M=1.94$, $SD=0.42$; *Middle-aged:* $M=2.20$, $SD=0.48$; *Elderly:* $M=2.57$, $SD=0.50$).

3.4 Between-group T-test analysis for Young, Middle-aged and Elderly

As shown in Table 2, independent-sample t-tests revealed no significant difference ($p>0.05$) in accuracy (C) between the Young group ($M=9.28$, $SD=0.78$) and the Middle-aged group ($M=9.25$, $SD=1.17$). However, participants in the Young group ($M=1.94$, $SD=0.42$) exhibited significantly shorter ($P=0.04$) reaction times (RT) than those in the Middle-aged group ($M=2.20$, $SD=0.48$).

Similarly, no significant difference ($p>0.05$) in accuracy was observed between the Young ($M=9.28$, $SD=0.78$) and Elderly ($M=8.91$, $SD=1.22$) groups. Nevertheless, participants in the Young group ($M=1.94$, $SD=0.42$) demonstrated significantly shorter ($p=0.002$) reaction time than those in the Elderly group ($M=2.57$, $SD=0.50$).

Accuracy did not differ significantly ($p>0.05$) between the Middle-aged ($M=9.25$, $SD=1.17$) and Elderly ($M=8.91$, $SD=1.22$) group. In contrast, the Middle-aged group ($M=2.20$, $SD=0.48$) showed significantly shorter ($p=0.03$) reaction time than the Elderly group ($M=2.57$, $SD=0.50$).

Table 1. The Accuracy and RT of Group A, Group B, and Group C

Group	Accuracy	RT (s)
Group A	9.26	2.23
Group B	9.24	2.18
Group C	9.72	2.09

Table 2. The C and RT of Young, Middle-aged, and Elderly

Group	Accuracy	RT (s)
Young	9.28	1.94
Middle-aged	9.25	2.20
Elderly	8.91	2.57

4. Discussion

This study explored the potential cognitive enhancement effects of 40 Hz binaural beats using the Stroop test. Multigroup analyses yielded several key findings. The ANOVA analyses revealed no significant differences in overall accuracy (C) or reaction time (RT) among Groups A, B, and C. However, t-tests indicated that participants in Groups A and B exhibited significantly lower accuracy compared with those in Group C. This finding suggests that exposure to 40 Hz music did not enhance cognitive inhibitory function relative to the no music control condition. Moreover, the reduced accuracy observed in both music groups compared to the silent condition implies that auditory stimulation - regardless of frequency - may have interfered with task performance. Analyses by age groups revealed no significant differences in accuracy across the Young, Middle-aged, and Elderly groups. However, reaction time was significantly shorter in the Young group than in the Middle-aged group, and shorter in the Middle-aged group than in the Elderly group. This pattern indicates a gradual age-related decline in cognitive inhibitory capacity which is consistent with an age-gradient effect.

Analyses showed that participants exposed to both 40 Hz and non-40 Hz auditory stimuli performed worse than those in the no-sound condition. The 40 Hz stimulation group not only failed to improve task performance but also demonstrated lower accuracy. It is contrary to the initial hypothesis. This result may be attributed to the nature of the auditory stimulation used. Previous studies have reported cognitive and neurophysiological benefits from 40 Hz stimulation primarily when employing non-auditory modalities or combining with other types of stimulation. For instance, Iaccarino et al. [7] demonstrated that one hour of daily 40 Hz light flicker for seven consecutive days significantly increased gamma power in the brains of Alzheimer's disease (AD) model mice. Similarly, Adaikkan et al.[12] found that combined 40 Hz light and sound stimulation enhanced gamma synchronization in the

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visual cortex, hippocampus, and auditory cortex. This combination reduced amyloid plaque deposition, and improved cognitive function. Other studies have shown that positive effects of 40 Hz stimulation on cognition typically occur under transcranial electrical or photic stimulation[13]. Therefore, it is plausible that purely auditory stimulation has a limited capacity to entrain gamma rhythms and enhance cognitive processing. This limitation likely explains why the 40 Hz group in the present study did not outperform other groups. Additionally, Reedijk et al.[14] reported that approximately 10 minutes of gamma-frequency stimulation induces only transient oscillatory effects which is insufficient to influence higher-order cognitive mechanisms. Hence, the brief duration of auditory exposure in this experiment may also have contributed to the absence of significant enhancement effects.

This study found that participants in the 40 Hz music stimulation group performed significantly worse on cognitive inhibition tasks compared to those in the silent control group. This impairment was likely caused by the brain's failure to entrain to the 40 Hz auditory frequency, resulting in the transformation of the auditory stimulus into neural noise. The synchronization of external periodic stimuli (e.g., 40 Hz beats) with endogenous neural oscillations underlies the theoretical mechanism through which frequency-based stimulation enhances gamma rhythms and cognitive performance. This mechanism depends on successful neural entrainment - the alignment of internal oscillatory activity with external rhythmic input. When entrainment fails, the external 40 Hz signal no longer acts as a "metronome". Instead, it becomes phase-misaligned with the brain's intrinsic gamma rhythms, thereby reducing the efficiency of neural information transmission. Consequently, the external rhythm did not translate into functional gamma synchronization but interfered with cognitive processing as phase noise. It led to poorer task performance and reduced accuracy. This interpretation aligns with the entrainment failure - noise hypothesis proposed by Klichowski and Król[15]. They consider that when external rhythmic stimulation fails to entrain the brain, the resulting phase noise disrupts the coherence of local microcircuits, increases the signal-to-noise ratio of neural representations, and forces the decision-making system to require more evidence accumulation and time to reach a response.

Data analysis further revealed an important age-related pattern: as age increased, participants' reaction time increased progressively, though accuracy remained stable. This pattern reflects the joint influence of strategic and physiological factors. When age increases, individuals tend to adopt more cautious decision-making strategies[16]. People would prioritiz accuracy over speed by gathering more information and verifying responses before committing to a choice. Such compensatory strategies increase reaction time while maintaining, or under certain conditions even improving, accuracy. In parallel, age-related declines in frontoparietal white matter fractional anisotropy (FA) and reduced neural conduction velocity contribute to diminished processing efficiency when older adults encounter cognitively conflicting information[17]. These results is consistent with the processing speed theory in the cognitive aging framework. The slowing of processing efficiency serves as the primary mediator of age-related cognitive decline[18].

Several limitations of the present study should be addressed in future research. First, the experiment lasted approximately five to ten minutes. The relatively short exposure duration may account for the observed failure of neural entrainment. Future research should consider extending the stimulation period or conducting repeated exposures across multiple sessions to enhance the likelihood of effective entrainment.. Second, the current study conducted group-based analyses across discrete age categories rather than modeling age as a continuous variable. Consequently, it was unable to estimate the precise trajectory or potential inflection points in the relationship between age and cognitive inhibition. Future work could adopt continuous age sampling and employ exponential or piecewise linear mixed-effects models to more accurately characterize the functional form of age-related cognitive change and overcome the extrapolation limitations of categorical group comparisons.

5. Conclusion

This study employed 40 Hz binaural beat audio and original music as experimental stimuli, with a no-music condition serving as the control group. Using the Stroop paradigm within a reaction time framework, it investigated how different auditory conditions influence participants' cognitive inhibition abilities. Data analyses revealed that both 40 Hz and original music exposure adversely affected participants' response accuracy. Furthermore, age-based analyses demonstrated a clear gradient in reaction time, which reveals the trend young < middle-aged < elderly. These results provide empirical support to processing speed theory[19]. The generalized slowing constitutes the primary mediator of age-related cognitive differences. The findings also extend the entrainment failure–noise hypothesis by generalizing"entrainment failure → phase noise" model from reasoning paradigms to inhibitory

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control[15]. This suggests that the proposed mechanism possesses cross-domain validity and provides a unified explanatory framework for previously inconsistent findings regarding the adverse effects of rhythmic stimulation.

Moreover, the present study demonstrates that “pure 40 Hz binaural beats × short stimulation duration × single auditory modality” not only fail to enhance cognitive inhibition performance but may also produce negative effects. This evidence offers a valuable reference for regulating cognitive enhancement products, neuro-music interventions, and age-related brain health applications - helping to prevent both resource misallocation and potential psychological burden. Finally, the observed continuous age - reaction time gradient highlights the necessity for both cognitive trainings to dynamically calibrate task difficulty and stimulus duration by age cohort, rather than adopting a uniform design across populations.

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