# EFFECTS OF BINAURAL BEATS ON COGNITIVE FUNCTIONS

by

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**Abstract**

Binaural beats have gained increasing interest, particularly regarding their potential effects on cognitive functions such as attention and memory. The present study explored the impact of different binaural beat frequencies (0 Hz, 7 Hz, and 40 Hz) on attention, memory, and mood. A within-subjects experimental design was used, with 48 participants completing a mood assessment, a reading comprehension task, and a global-local attentional processing task while listening to each of the three binaural beat sounds (sound order was counterbalanced). The results suggested that 40 Hz binaural beats significantly enhanced reading comprehension accuracy and reduced accuracy differences between congruent and incongruent figures in the global-local task, consistent with a narrowed scope of attention. In contrast, the 7 Hz and control conditions showed no significant effects, and there were no notable effects on mood for any binaural beat sounds. The cognitive effects align with prior work broadly, a 40 Hz binaural beat is beneficial for attention and memory, but the mood effects did not replicate. Given these results, 40 Hz beats may have improved cognition via neural entrainment, as gamma frequency power has been associated with cognitive performance, however, the use of EEG or fMRI would be important to better understand the underlying mechanisms. Moreover, their potential long-term effect is also worth studying. In conclusion, although this study supports the potential cognitive benefits of 40 Hz binaural beats, more research is necessary to further explore and expand these findings.



*Keywords:* binaural beats, cognitive functions, attention, memory, mood

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## Introduction

The perception of sound plays an important role in daily life. Hearing not only supports individuals on a physical and social level – facilitating communication, gathering information, and detecting potential dangers – but also significantly impacts psychological well-being (e.g., Goldsby et al., 2022). Additionally, likely due to the presumed association between certain sounds (e.g., music) and well-being, many individuals prefer listening to sounds while doing other things, such as studying, as this is believed to help concentration and memory in some contexts (e.g., see Goltz & Sadakata, 2021). Studies have partially corroborated these perceptions, findings that sounds such as music, white noise, and binaural beats can positively influence cognitive function and mood in some contexts. For example, Särkämö and colleagues (2008) found that listening to music in the early stages of stroke recovery supported cognitive rehabilitation and helped reduce negative emotions. Moreover, interest in binaural beats is steadily growing among researchers, although the effects of binaural beats on both mood and cognitive functioning remain understudied. This study therefore aimed to examine the impact of binaural beats on cognitive functions and mood.

### Binaural Beats

Binaural beats are an auditory phenomenon that occur when two slightly different acoustic frequencies are presented to each ear (for example 250 Hz to the left ear and 290 Hz to the right ear). This creates the perception of a single tone with a "beating" frequency that reflects the difference between the two frequencies – in this case, 40 Hz (Ingendoh et al., 2023). Given that input from the two ears is first combined subcortically, at the superior olivary complex (Perez et al., 2020), binaural beats are thought to influence neural activity more centrally (subcortical and cortical processing), rather than peripherally (at the level of the cochlea). This perceived frequency does not exist as a physical sound, as is the case when two slightly different frequencies are presented to the *same* ear (creating a physical amplitude modulation of "beats" at the level of the cochlea) but is instead a virtual auditory phenomenon generated by the brain. To experience binaural beats, headphones or similar devices are necessary to ensure that each ear hears its respective frequency independently; otherwise, the combined sound will mask the binaural beat effect.

Importantly, binaural beats are hypothesized to lead to *neural entrainment* at the rate of the beating frequency (e.g., see Ingendoh et al., 2023 for a review), meaning the natural oscillatory patterns of neural activity phase lock to the frequency of the binaural beat. This is significant because a large body of literature has associated different neural oscillations with different cognitive (e.g., Obleser & Kaysar, 2019) and affective (e.g., Trost et al., 2014) states, meaning that binaural beats might represent a low-cost means of manipulating cognitive and affective states via neural entrainment.

Sharma and colleagues (2017) stated that binaural beats at different frequencies can influence various states of consciousness in listeners via neural entrainment, presumably because different neural oscillation frequencies have been associated with different psychological states. Researchers have categorized these brainwave frequencies into specific bands: delta (0.1–4 Hz), theta (4–8 Hz), alpha (8–12 Hz), beta (12–30 Hz), and gamma (30–80 Hz) (Borges, Arantes, & Naves, 2023). Higher frequencies are linked to increased alertness and awareness, whereas lower frequencies are linked to relaxation. For instance, theta frequencies are associated with deep relaxation, meditation, and problem-solving, whereas beta frequencies correspond to wakefulness and normal alertness. These findings highlight the potentially distinct effects of different binaural beat frequencies, emphasizing the importance of distinguishing between them in experimental studies.

## Influence of Binaural Beats on Cognitive Functions

Research on the impact of binaural beats on cognitive functions has primarily focused on how binaural beats influence attention. Selective attention is a critical process that affords individuals the ability to select goal-relevant information and inhibits the processing of goal-irrelevant stimuli (e.g., see Lindsay, 2020 for a review). It is a core component of executive functions, closely related to other cognitive constructs such as working memory (e.g., Oberauer, 2019). Additionally, attention can help with emotional regulation by directing focus on positive or beneficial information (Wadlinger, & Isaacowitz, 2011), providing an important link between attention and affective state. Selective attention has also been linked with gamma frequencies in EEG (e.g., Gruber et al., 1999; Müller et al., 2000), which provides a plausible mechanism for how binaural beats might enhance attentional processing.

Despite this potential connection between binaural beats, neural entrainment, and attentional processing, the research examining whether binaural beats can enhance attention is mixed. Leistiko and colleagues (2024) found that 40 Hz binaural beats did not significantly enhance attention. Conversely, Engelbregt and colleagues (2021) reported that although without evidence of neural synchronization, listening to 40 Hz binaural beats can improve attention. Reedijk and colleagues (2015) found that high-frequency binaural beats can enhance visual attentional control, as demonstrated using the attentional blink task.

Colzato et al. (2017) assessed how binaural beats influenced both affect and attentional processing, thus providing an important foundation for the present work. In their study, 36 participants were randomly and evenly divided into two groups: one group that listened to a 40 Hz high-frequency binaural beat, and a control group that listened to a 340 Hz single tone with no binaural beats (i.e., a 0 Hz beat control). Using a global-local attentional processing task and an affective measure assessing valence and arousal, the researchers discovered that gamma-frequency binaural beats significantly increased arousal levels and led to a narrower focus of attention. The global-local task used in this study measures how efficiently individuals process global versus local features of hierarchically structured visual stimuli. It is closely tied to the "global precedence" effect, in which global features are processed faster than local features and the "interference effect", where global stimuli hinder recognition of local targets but not the reverse (Poirel et al., 2008). Generally, processing global information is thought to rely on broader attention, whereas processing local information demands narrower, more focused attention. However, the study by Colzato and colleagues (2017) exclusively examined high-frequency binaural beats relative to no binaural beats, making it unclear whether *any* binaural beats would yield similar results, or whether these arousal and attentional effects are limited to higher frequency binaural beats. This limitation highlights the need for further exploration into the broader effects of binaural beats on cognitive processes.

Building on the existing focus on the relationship between binaural beats and attention, it is important to consider the potential impact on other cognitive domains. Given the close associations between attention and memory (e.g., Cowan et al., 2024), in addition to the anecdotal use of binaural beats for improving studying and retention of learned material, memory may also be an important cognitive construct to assess in the context of binaural beats. Similar to the effects of binaural beats on attention, the effects of binaural beats on memory are mixed. For example, Beauchene and colleagues (2017) found that by examining 34 healthy participants' performance on the N-back working memory task, only binaural beats at 15 Hz (beta frequency) improved individual participants' accuracy, modulating cortical frequency response and altering the strength of cortical network connectivity under different circumstances during the task. However, Ortiz and colleagues (2008) found in a study of 20 participants that auditory stimulation at 5 Hz (theta) frequency produced coupling of brain activity, which increased the ability to memorize immediate speech. Shekar and colleagues (2018) found in a study of 40 participants that after experiencing binaural beats at alpha and gamma frequencies, the ability to memorize immediate speech increased. Gamma frequency binaural beats participants experienced a decrease in both auditory and visual reaction times, as well as an increase in memory scores and attention. Although the results of some experiments may be contradictory, there generally seems to be evidence for binaural beats improving memory processes. The differences across studies with respect to the binaural beat frequencies and the memory measures make broader conclusions difficult.

**Influence on Mood**

Mood is a temporary, conscious emotional state typically influenced by external factors (Chaieb et al., 2015). It significantly affects various aspects of life, including health, behavior, and overall well-being. A positive mood is strongly linked to increased efficiency, better physical health, and improved interpersonal relationships, often leading to more favorable outcomes.

Research has shown that binaural beats can influence mood. For instance, Lane and colleagues (1998) studied 29 participants who were exposed to pink noise containing simple tones, or binaural beats in the beta range (16–24 Hz), or the theta range (1.5–4 Hz) during a 30-minute visual vigilance task. The study found that beta-frequency binaural beats improved task accuracy and reduced negative affect. More recently, Shakya and colleagues (2024) conducted a study with 40 participants who listened to binaural beats at 40 Hz. Using the 32-item Brunel Mood Scale and the Stroop test, the researchers observed that binaural beats decreased negative emotions, enhanced positive moods, and improved cognitive performance. Notably, the effects appeared gender-specific: women experienced greater increases in “happiness” and “calmness”, whereas men showed more significant cognitive performance improvements. Despite these findings, there remains a relative lack of research directly comparing the effects of different binaural beat frequencies on mood.

**Relationship between Cognitive Functions and Mood**

Numerous studies have shown that various types of sound can enhance mood and improve cognitive performance. One of the most well-known phenomena in this area is the Mozart Effect, which refers to an increase in spatial reasoning abilities after listening to Mozart's music (Rauscher et al., 1993). This discovery surprised many researchers and prompted further investigation into its underlying mechanisms. A prominent explanation is that Mozart's music induces a positive mood and heightens arousal, which in turn enhances spatial performance. In their study, Thompson et al. (2001) recruited 24 participants to listen to either a Mozart sonata or an Albinoni Adagio. The results revealed that participants who listened to Mozart scored higher on spatial ability tests and reported higher levels of positive emotions and arousal compared to those who listened to Albinoni. These findings highlight how mood can interact with cognitive functioning.

Arousal, memory, and attention are interconnected and widely studied topics. Turkileri and colleagues (2021) manipulated participants' arousal levels using a fear-conditioned tone (CS+) and a neutral tone (CS−) that had not been paired with electrical stimulation. Their analysis of whether participants could accurately identify a target key within a scene revealed that higher arousal enhanced target detection ability. This suggests that arousal enhances the ability of long-term memory to direct attention, with higher arousal linked to improved memory performance and more focused attention. Similarly, Lee and Sternthal's (1999) research demonstrated that positive mood could enhance learning. Their experiments showed that participants in a positive mood were better at learning brand names compared to those in a neutral mood, highlighting the connection between positive mood and memory. These findings thus point to a secondary mechanism through which binaural beats might influence cognitive performance: by increasing positive mood and arousal.

### The Present Study

The current study explores how binaural beats administered at different frequencies influence attention size, memory and mood, along with the relationship between mood state and cognitive functions. Based on the previous studies, the study primarily focused on comparing the effects of theta (7 Hz) and gamma (40 Hz) binaural beat frequencies, comparing these conditions to a control condition in which participants listen to a single 250 Hz tone with no binaural beats (i.e., a 0 Hz control condition). Moreover, unlike many previous studies, the current study utilized a within-subject design with the order of the sounds (40 Hz binaural beats, 7 Hz binaural beats, 0 Hz control) counterbalanced across participants. The present study also aims to investigate the relationship between mood state and cognitive functions under different binaural beat conditions.

In line with previous studies, the central hypotheses are: 1) Gamma frequency (40 Hz) binaural beats will increase arousal, leading to greater focus, smaller attention size, and improved memory; 2) Theta frequency (7 Hz) binaural beats will promote relaxation (i.e., reduce arousal), leading to an expanded attention size, and also enhance memory; 3) Increases in positive affect and arousal, regardless of binaural beat condition, will be associated with improved memory and focused attention span.

## Method

### Participants

There were 48 participants, consisting of 12 men, 35 women, and 1 who preferred not to answer, recruited by researchers primarily through the Sona (https://sona-systems.com) research participants system. Their age ranged from 18 to 37 years old (*M* = 20.00, *SD* = 3.64). There were 24 different counterbalancing conditions in total—six for the three different binaural beat sequences and four for the different positions of the local and global cues. We therefore aimed to recruit 48 participants to ensure an equal number of people in each condition, thus making any observed effects of binaural beats or performance in the global-local task unable to be explained by the specific ordering of sounds or the specific configuration of the global-local task. All participants provided informed consent, and the present research was approved by the Huron Research Ethics Board (18S-202411).

**Materials**

The Sound Discrimination Task was developed by the researchers to assess auditory perception ability – specifically related to the explicit discrimination of the three types of sounds used in the present study. In this task, participants listened to two short (1 s) auditory recordings and had to determine whether they were the same or different. The recordings included a 7 Hz binaural beat, a 40 Hz binaural beat, and a 0 Hz control beat. The session consisted of 12 trials—six with different stimuli and six with identical stimuli. For instance, a participant might hear a 7 Hz beat followed by a 40 Hz beat and needed to decide if they were the same or different. Each participant receives a discrimination accuracy score, ranging from 0 (all incorrect) to 1 (all correct).

The study utilized the 12-item Hedonic and Arousal Affect Scale (HAAS) (Roca et al, 2023) as the measurement of mood state. The test includes 12 terms, each assigned a specific valence (positive or negative) and arousal level (high or low). There were four categories: three terms were positive and high-arousal, three were positive and low-arousal, three were negative and high-arousal, and three were negative and low-arousal. For instance, "Interested" is positive and high-arousal, "Calm" is positive and low-arousal, "Guilty" is negative and high-arousal, and

“Tired” is negative and low-arousal. Responses were measured on a 5-point Likert scale (0: *Not at all*, 4: *Extremely*). Participants completed the test four times: at the beginning of the study, as well as after listening to each of the three sounds (i.e., at the end of each sound block). For each assessment, they received an average score for each of the four categories (positive-high, positive-low, negative-high, and negative-low).

Ten validated reading comprehension passages and questions developed by Vermeiren et al. (2023) were used in this study. One of the passages (detailing the multiple intelligences theory of Howard Gardner) was presented as practice. The remaining nine passages were divided into three sets of three passages each, with each set of three passages being presented at the beginning of each block. Sets of passages had a fixed order for all participants (e.g., all participants received the same three passages for the first block, the same three passages for the second block, etc.); however, because sound ordering varied across participant and because there was a balanced number of participants across all sound orderings, any inherent differences in difficulty for the passage sets could not explain. Each passage was associated with three multiple-choice questions with four possible responses, meaning there were nine total multiple-choice questions associated with the passages for each block. Participants received a reading comprehension accuracy score for each block, reflecting the proportion of correct responses, where a score of 1 indicates all correct answers, a score of 0 indicates all incorrect answers, and a score of 0.25 indicates chance performance.

The global-local task was based on Colzato and colleagues (2017). The global-local task contained larger squares or rectangles, which were made up of either smaller squares or rectangles. If a larger square consisted of smaller squares or larger rectangles consisted of smaller rectangles, the shapes would be considered *congruent*. In contrast, if a larger square consisted of small rectangles or a larger rectangle consisted of smaller squares, the shapes would be considered *incongruent*. Half of the trials were congruent, and the other half were incongruent. Although participants received equal numbers of congruent and incongruent trials, this was not the feature to which they responded. Rather, participants had to press a designated key (Q or P) to categorize either the global or local shape of the object (i.e., to categorize the larger or smaller shapes as either squares or rectangles). On each trial, participants would first see a central fixation line (1000 ms). Then, participants would see two *cues*, which were left and right lateralized and appeared either above or below the central fixation line and indicated to participants whether they should respond to the global or local features of the to-be-categorized shape. For example, if a participant saw a small square and small rectangle above the central fixation, and the square was to the left of the central fixation and the rectangle was to the right of the central fixation, this would indicate that participants should categorize the upcoming shape based on its local features (pressing Q if the local features were squares and P if the local features were rectangles). The mapping of specific shapes (squares, rectangles) to buttons (Q, P), as well as the mapping of specific cues (local, global) to screen positions (top, bottom) was counterbalanced across participants, resulting in four versions of the task. The cues were presented for a variable amount of time (between 400 and 600 ms). Participants had a fixed amount of time (2000 ms) to categorize the presented shape based on either its local or global features, and there was a variable inter-trial interval (3000 ms minus the combined duration of the cue and the response time) to ensure that the global-local task took a comparable amount of time, regardless of how long it took participants to respond to the shapes. Performance was operationalized in terms of both mean accuracy and response time (for correct responses) for each of the four trial types (global congruent, global incongruent, local congruent, local incongruent) for a given block.

**Procedure**

Interested participants signed up for the study through the Huron University Sona website systems. At the time of their scheduled session, participants were directed to the psychology lab at Huron to take part in the experiment. After reading the Letter of Information and providing informed consent, participants began the study on a designated lab computer. Firstly, they provided demographic details, including their age and gender. Following the demographic information collection, participants completed the 12 trials of the sound discrimination task, designed to assess how well participants could distinguish the difference between beats sounds. Next, participants completed the initial HAAS mood survey, which was used as a baseline measurement. Following this, participants completed training sessions for both the reading comprehension task and global-local task. In the reading comprehension practice, all participants were presented with the same passage for 45 seconds, which was then immediately followed by three multiple-choice questions (with feedback provided after each response). Participants were instructed that in the main study, each passage would also be shown for 45 seconds; however, there would be a delay in the presentation of the comprehension questions and participants would not receive feedback as to whether their responses were correct or incorrect. Following the reading comprehension practice, participants completed the global-local practice. Specifically, participants were first separately trained to respond to the global (24 trial, with feedback) and local (24 trial, with feedback) features of the shapes. Following this separate training, participants completed a combined practice session (72 trials, with feedback) to become accustomed to switching between the global and local judgments. In both the combined practice, as well as in the main assessments, we opted to create smaller blocks of global and local judgments (4 trials each) before switching to the other cue, as opposed to completely randomizing the presentation of global and local cues, as this was also done by Colzato and colleagues (2017).

Following the global-local practice, participants began formal testing. The script began playing either the 40 Hz high-frequency binaural beats, 7 Hz low-frequency binaural beats, or control (0 Hz) sound, with the specific sound being played depending on the counterbalancing condition. Participants then read three short passages, each taking 45 seconds, while listening to the audio, and afterward, completed 80 trials of the global-local task, which lasted about 4 minutes. At the end of the task, they would answer questions related to the passages they read earlier (nine total questions, presented in a randomized order), as well as reassessed their mood using the HAAS, before proceeding to the next block of trials (which would contain a different sound). Given that each sound was 10 minutes in duration, the sounds played throughout the reading comprehension and the global-local task and ended either during the reading comprehension questions or the HAAS mood scale, depending on how quickly participants answered the reading comprehension questions. This process was repeated three times to ensure each participant was exposed to high-frequency binaural beats, low-frequency binaural beats, and the control sound. After completing all three conditions, participants were debriefed and compensated for their participation.

# Results

## Sound Discrimination Accuracy

A one-sample *t*-test was used to analyze the accuracy of the sound discrimination test. The average performance of the participant cohort ($M = 0.83$, $SD = 0.13$) was higher than the chance estimate of 0.50, $t(47) = 17.20$, $p < .001$, $d = 2.48$, demonstrating that the participants in the study were able to explicitly differentiate the three sound conditions used in the present study.

**Reaction Time for Global-Local Task**

For the response time measures, five participants' data was excluded as they were missing valid reaction times from at least one of the categories (congruent local, congruent global, incongruent local, incongruent global) for at least one of the blocks. The remaining data were analyzed using a 2 (congruent, incongruent) x 2 (global, local) x 3 (40 Hz binaural beat, 7 Hz binaural beat. 0 Hz control) repeated measures ANOVA, with response time as the dependent variable.

There was no significant main effect for different beat conditions, $F(2, 84) = 0.84$, $p = .433$, $\eta_p^2 = .02$. However, there was a significant main effect for global-local cues, indicating participants were slower to categorize local ($M$ = 738 ms, $SE$ = 22.6) versus global ($M$ = 709 ms, $SE$ = 25.6) shapes, $F(1, 42) = 10.33$, $p = .003$, $\eta_p^2 = .20$. There was also a significant main effect for congruence, $F(1, 42) = 33.92$, $p < .001$, $\eta_p^2 = .45$, demonstrating participants were faster to respond to congruent shapes ($M$ = 695 ms, $SE$ = 21.7) compared to incongruent shapes ($M$ = 751 ms, $SE$ = 26.5).

Furthermore, there was no significant interaction between beat condition and global-local cues, $F(2, 84) = 1.13$, $p = .327$, $\eta_p^2 = .026$. Similarly, there was no significant interaction between beat condition and congruence, $F(2, 84) = 0.56$, $p = .573$, $\eta_p^2 = .013$. There was no significant interaction between global-local cues and congruence, $F(1, 42) = 2.22$, $p = .144$, $\eta_p^2 = .050$. Additionally, there was no significant interaction between beat condition, global-local cues, and congruence, $F(2, 84) = 1.20$, $p = .306$, $\eta_p^2 = .028$.

**Accuracy for Global-Local Task**

Similar to the reaction time analysis, accuracy data from the global-local task was analyzed using a 2 (congruent, incongruent) x 2 (global, local) x 3 (40 Hz binaural beat, 7 Hz binaural beat, 0 Hz control) repeated measures ANOVA, with accuracy as the dependent variable. Unlike the response time model all participants ($n$ = 48) were included.

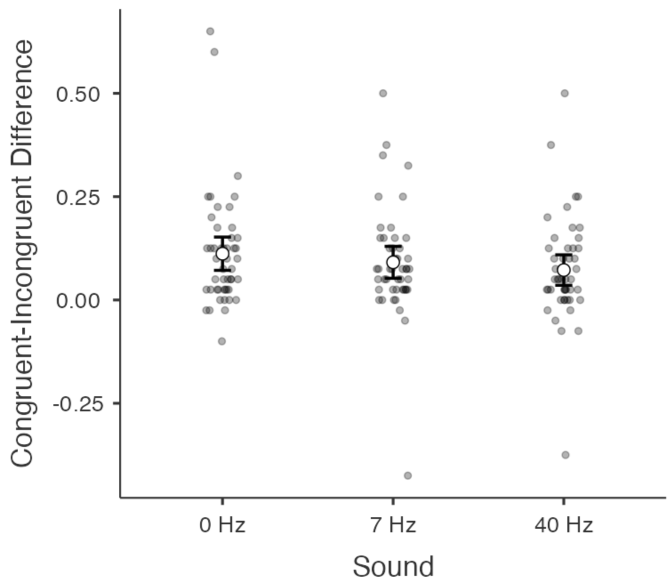
There was no significant main effect for different beat conditions, $F(2, 94) = 0.66$, $p = .520$, $\eta_p^2 = .01$, suggesting that overall accuracy was not influenced by different binaural beats. Moreover, there was no significant main effect for global-local cues, indicating accuracy for global and local tests did not differ significantly, $F(1, 47) = 1.18$, $p = .283$, $\eta_p^2 = .02$. However, there was a significant main effect for congruence, $F(1, 47) = 28.11$, $p < .001$, $\eta_p^2 = .37$, with accuracy for congruent shapes ($M$ = 0.91, $SE$ = 0.03) being significantly higher than accuracy for incongruent shapes ($M$ = 0.82, $SE$ = 0.02).

Furthermore, there was no significant interaction between beat condition and global-local cues, $F(2, 94) < .01$, $p = 1.000$, $\eta_p^2 = .00$. Similarly, there was no significant interaction between global-local cues and congruence, $F(1, 47) = 0.77$, $p = .386$, $\eta_p^2 = .02$. There was no significant interaction between beat condition, global-local cues and congruence, $F(2, 94) = 0.70$, $p = .499$, $\eta_p^2 = .02$.

However, there was a significant interaction between beat condition and congruence, $F(2, 94) = 3.83$, $p = .025$, $\eta_p^2 = .08$. Post-hoc tests using difference scores (congruent minus incongruent) as the dependent variable suggested that, compared to the 0 Hz control condition ($M_{\text{congruent}} = 0.927$, $M_{\text{incongruent}} = 0.815$), the 40 Hz beat condition ($M_{\text{congruent}} = 0.883$, $M_{\text{incongruent}} = 0.811$) had a smaller congruent-incongruent difference ($p = .036$). Importantly, the nonsignificant main effect of sound condition in this model, as well as nonsignificant post-hoc comparisons of congruent trial accuracy across the three sound conditions suggested that this effect could not be simply explained in terms of overall lower accuracy in the 40 Hz beat condition.

**Figure 1**

Estimated marginal means for congruent-incongruent difference and beat conditions.



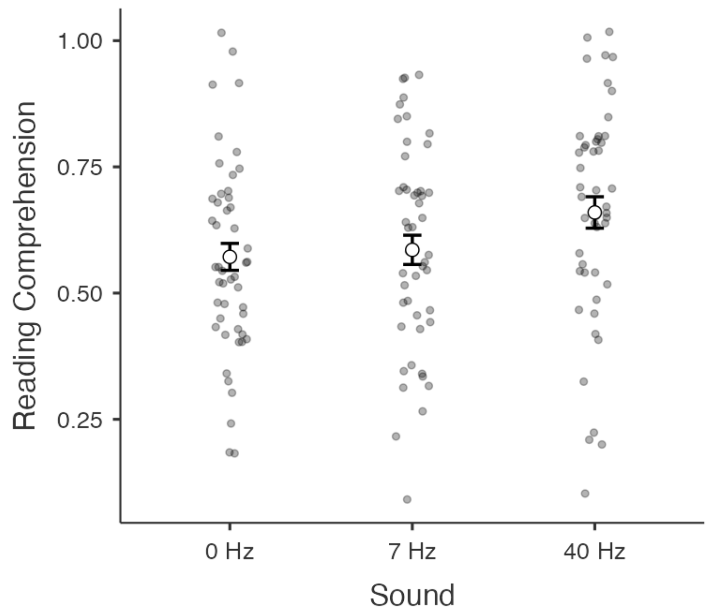

**Reading Comprehension Accuracy**

The reading comprehension data were analyzed using a one-way repeated measures ANOVA, with beat condition (40 Hz binaural beat, 7 Hz binaural beat, 0 Hz control sound) as the independent variable and accuracy of reading comprehension test as dependent variable.

There was a significant main effect of beat condition, $F$ (2, 94) = 5.52, $p$ = .005, $\eta_p^2$ = .11, plotted in Figure 2. Post-hoc test results revealed that 40 Hz condition ($M$ = 0. 66, $SE$ = 0.03) had significantly higher accuracy level than both the 0 Hz control condition ($M$ = 0.57, $SE$ = 0.03), $p$ = .011, and the 7 Hz beat condition ($M$ = 0.59, $SE$ = 0.03), $p$ = .043.

**Figure 2**

Estimated marginal means for reading comprehension accuracy and beat conditions.




**Mood Measurements**

The mood data were analyzed using a 2 (positive, negative) x 2 (high arousal, low arousal) x 4 (Baseline, 40 Hz binaural beat, 7 Hz binaural beat, 0 Hz control sound) repeated measures ANOVA, with mood rating as the dependent variable. Unlike the other analyses, an additional level was incorporated in the mood analyses as participants completed a baseline assessment, prior to listening to any sounds.

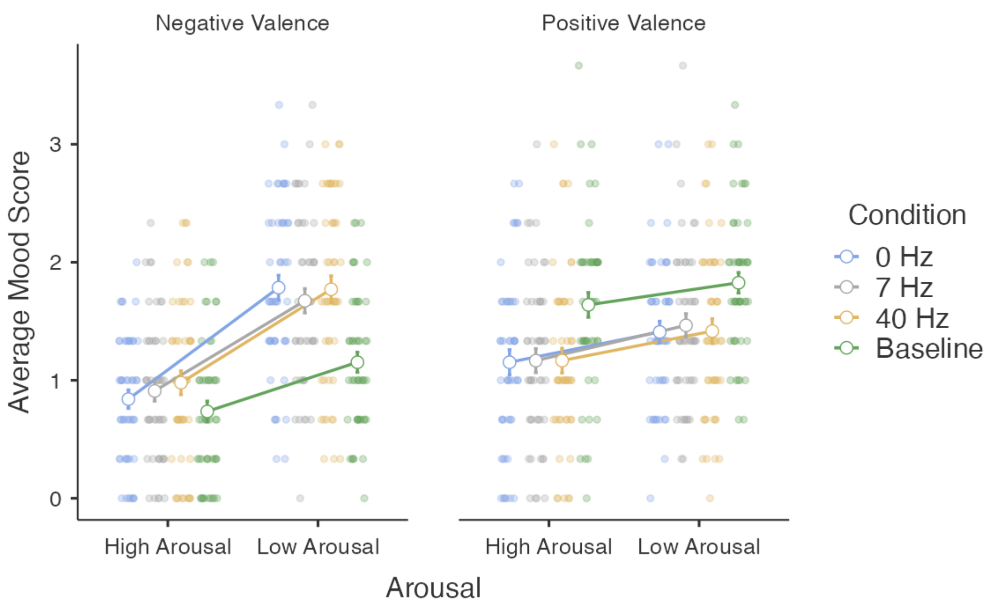
There was no significant main effect of conditions, $F(3, 141) = 0.68$, $p = .564$, $\eta_p^2 = .01$. The overall mood ratings did not differ between different frequencies of binaural beats or the baseline measurement. Moreover, there was no significant main effect for valence, $F(1, 47) = 2.66$, $p = .110$, $\eta_p^2 = .05$. However, there was a significant main effect for arousal level, $F(1, 47) = 46.27$, $p < .001$, $\eta_p^2 = .50$, with participants rating low arousal items higher than high arousal items overall.

All two-way interactions were significant. There was a significant interaction between condition and valence, $F(3, 141) = 24.62$, $p < .001$, $\eta_p^2 = .34$, between condition and arousal, $F$(3,

141) = 4.18, $p$ = .007, $\eta_p^2$ = .08, and between valence and arousal, $F(1, 47)$ = 31.78, $p$ <.001, $\eta_p^2$ = .40. There was also a significant three-way interaction between beat condition, valence, and arousal, $F(3, 141)$ = 4.18, $p$ = .007, $\eta_p^2$ = .08. However, based on Figure 3 and post-hoc tests, all significant differences were driven by the baseline measurements. In other words, at baseline, participants had higher positive valence and high arousal ratings, which significantly decreased throughout the study, potentially reflecting increased boredom and fatigue.

**Figure 3**

Estimated marginal means for interaction between arousal, beat conditions, and valence.




*Note*: Error bars represent standard errors of the mean.

## Discussion

### Present Results

The present study hypothesized that (1) gamma frequency (40 Hz) binaural beats would increase arousal, leading to greater focus, smaller attention size, and improved memory; (2) theta frequency (7 Hz) binaural beats would promote relaxation (i.e., reduce arousal), leading to an expanded attention size, and also enhance memory; and (3) increases in positive affect and arousal, regardless of binaural beat condition, would be associated with improved memory and focused attention span. The present findings provided partial support for these hypotheses, particularly for the first hypothesis related to 40 Hz binaural beats. Analysis of reading comprehension accuracy revealed a significant main effect, with post-hoc tests showing a significant improvement in participants' memory under the 40 Hz binaural beat condition relative to both the 7 Hz and 0 Hz conditions. Additionally, the 40 Hz binaural beat influenced performance on the global-local task, as indicated by a smaller difference between congruent and incongruent conditions. While the observed effects in the global-local task align with changes in attention, they differ from previous findings by Colzato et al. (2017). Contrary to the hypotheses, no effect of the 7 Hz binaural beat on attention or memory was found. Moreover, binaural beats did not influence mood, and thus the specific question of whether any cognitive differences were mediated by mood was not considered.

### Exploration of 40 Hz Binaural Beats

Gamma-band oscillations in the brain (approximately 30–100 Hz) are closely linked to cognitive processes, with memory-related activity appearing to be the most prominent and potentially foundational for other functions, including attention, binding, object representation, and language (Herrmann et al., 2010). Furthermore, a study by Nissim et al. (2023) using transcranial alternating current stimulation (tACS), a noninvasive technique that modulates cortical oscillations through small electrical current oscillations, demonstrated that gamma oscillations provided by tACS were able to augment gamma power in the brain and enhance cognition function in mild cognitive impairment (MCI) and Alzheimer's disease (AD) individuals. Their findings supported that gamma tACS can improve cognitive and memory processes that are impaired in individuals with MCI and AD. Consequently, gamma frequency plays a significant role in cognitive function, and researchers suggest that increasing gamma brain wave activity, whether through gamma tACS or exposure to a 40 Hz external stimulus, may benefit cognitive performance.

Gamma frequency (40 Hz) binaural beats are considered a way to induce gamma brain waves. The theoretical foundation of studies examining the effects of binaural beat stimulation is the brainwave entrainment hypothesis. This hypothesis suggests that external auditory stimulation at a specific frequency induces the brain's electrocortical activity to oscillate at the same frequency (Ingendoh et al., 2023). Research by Jirakittayakorn and Wongsawat (2017) demonstrated that exposure to a 40 Hz binaural beat enhances gamma oscillations in the temporal, frontal, and central brain regions, with a particularly notable effect after several minutes of listening. Moreover, Wang et al. (2022) found that exposure to 40 Hz binaural beats elicited frequency-following responses, leading to improved performance on a working memory task. In other words, their findings support the idea that neural oscillations tend to synchronize with the frequency of the received binaural beat and lead to improvement in cognitive performance. Therefore, in line with previous research, although the present study did not employ EEG or other brain activity monitoring equipment, the observed improvements in reading comprehension accuracy and the reduced accuracy difference between congruent and incongruent shapes in the global-local task can be plausibly attributed to neural entrainment at 40 Hz induced by the external binaural beats.

**Comparison Between Present Results and Colzato et al. (2017)**

Although the explanation of neural entrainment is supported by previous research, it is important to note that the performance differences observed in the present study's global-local task differ from those reported by Colzato et al. (2017). In the current study, the 40 Hz condition significantly reduced the accuracy difference between congruent and incongruent shapes. In contrast, Colzato et al. (2017) found that under the 40 Hz condition, the difference in reaction times between global and local cues decreased, leading to a smaller "global precedence" effect. Thus, the present findings were driven by accuracy differences, whereas the results of Colzato et al. (2017) were driven by response time differences. One possible explanation for this discrepancy is the different "timeout" windows (i.e., the amount of time given for a response) between the two studies. Notably, Colzato et al. (2017) reported inconsistent timeout values—stating 1200 ms in Figure 1 but 2500 ms in the main text. To address this inconsistency, the present study adopted an intermediate timeout value of 2000 ms. However, according to the speed-accuracy tradeoff principle, a more restricted response window (i.e., allowing participants less time to respond) increases the likelihood of errors (Heitz, 2014). As a result, this may have shifted the observed effects from reaction time to accuracy – particularly if Colzato and colleagues (2017) indeed allowed 2500 ms for a response.

Despite the differences between the two studies, there is a notable similarity: under the 40 Hz binaural beat condition, both studies observed an attenuation (i.e., "closing of the gap") in typical performance differences in the global-local paradigm. In Colzato et al. (2017), the global precedence effect suggests that processing local cues requires greater effort for decision-making. Similarly, in the present study, the incongruent figures, due to their differing shapes, also demanded more cognitive effort for accurate responses. Both tasks require cognitive control, which is essential for the flexible allocation of mental resources in goal-directed behavior (Mackie et al., 2013).

A key component of cognitive control in such scenarios is executive attention. The executive attention network, which involves the anterior cingulate and lateral prefrontal areas, is strongly activated in situations that require attentional control—particularly when conflicts arise between competing stimulus dimensions (Rueda et al., 2005). Given the presence of such conflicts in both studies, executive attention would likely have been engaged to redirect focus to the appropriate cues. As a result, both Colzato et al.'s findings and those of the present study suggest that gamma-frequency binaural beats may enhance inhibitory control in the presence of conflicting information, ultimately benefiting executive attention. However, further research is needed to explore the precise effects of binaural beats on executive attention.

## Limitations

### *Mood Results*

The present study did not support any mood-related effects as a function of binaural beat condition. This contrasts with previous findings by Colzato et al. (2017), who reported a significant increase in arousal levels between the first and second measurements for participants who listened to 40 Hz binaural beats. One potential explanation for this discrepancy could be the differences between studies in terms of how mood was assessed. Specifically, the present study used a conceptually similar but different scale compared to Colzato et al. (2017). It utilized the 12-item Hedonic and Arousal Affect Scale because it is relatively brief and separates valence from arousal, which was important given the findings of Colzato et al. (2017) on arousal but not mood. Another possible explanation of the differences between the studies relates to choices of experimental design. Specifically, the present study used a within-participant design, whereas Colzato and colleagues (2017) used a between-participant design. However, due to the within-participant design, participants completed this scale four times (at baseline and after each sound condition), increasing the likelihood of general fatigue. This is supported by the findings, which showed a trend of increased negative valence and decreased arousal in later blocks compared to baseline. To address this issue in future research using a within-participant design, it would be beneficial to assess valence and arousal with a shorter and simpler measure to minimize the tediousness of repeatedly completing the same questionnaire.

### ***Other Limitations***

As previously mentioned, the setting of the timeout window may have been a minor limitation, at least with respect to directly replicating the observed findings of Colzato et al. (2017). Even small methodological differences can lead to inconsistencies in experimental outcomes. Future studies could improve comparability by replicating one of the exact timeout values used in previous research.

Additionally, attention is a complex construct with multiple subtypes, and different attention tasks may produce varying results. For example, if 40 Hz binaural beats influence directed attention and, consequently, performance on tasks requiring cognitive control, then we would expect to observe performance differences across different auditory conditions. Thus, to further investigate executive attention, employing tasks such as the Stroop test, Eriksen Flanker Task, or similar assessments could provide deeper insights into the effects of binaural beats.

Furthermore, increasing the listening duration for the binaural beats may enhance the observed effects. As noted in a previous study by Jirakittayakorn and Wongsawat (2017), the most notable changes in brain activity occurred after approximately 15 minutes of exposure to binaural beats. In contrast, participants in the current study only listened to the audio for 10 minutes, which may have been insufficient to elicit measurable changes in cognitive tasks.

Therefore, future research could improve based on this by extending the listening duration to potentially produce more significant and meaningful outcomes.

## Future Directions

It is evident that further research on binaural beat is necessary, particularly regarding the durability of its effects on cognitive function. Most existing studies have focused on the immediate effects of binaural beats; for example, comparing performance before and after exposure. However, it remains unclear whether these cognitive improvements persist over time and whether periodic listening to binaural beats can produce long-term benefits. If such long-term effects exist, binaural beats could potentially be explored as a form of sound therapy. For instance, given that both the present study and Colzato et al. (2017) suggest that 40 Hz binaural beats may enhance executive attention, future research could investigate whether 40 Hz-based sound therapy could be beneficial for individuals with attention deficit hyperactivity disorder.

Moreover, since the effects of binaural beats are based on the brainwave entrainment hypothesis, incorporating neuroimaging techniques such as fMRI and EEG in future studies could provide a clearer understanding of the neural mechanisms underlying these effects. Overall, given the complexity of the human brain and cognitive functions, more work remains necessary to be done in the study of binaural beats. Further research is needed to determine their long-term impact, potential therapeutic applications, and underlying neural processes.

## Conclusion

The present study found that 40 Hz binaural beats significantly improved reading comprehension accuracy and decreased the accuracy difference between responding to congruent and incongruent shapes in an attentional task, suggesting a potential role in enhancing cognitive performance. While these findings align with some previous research (e.g., Colzato et al., 2017), they also failed to replicate other findings – particularly binaural beat induced changes in self-reported arousal. Despite the promising findings that 40 Hz binaural beats may enhance aspects of cognitive performance, the study has certain limitations. For instance, the within-subjects design may have increased statistical power to detect some effects, but inadvertently suppressed mood-related effects due to the repetitive and fatiguing nature of the study. Future research could explore the long-term effects of binaural beats and assess their potential as a cognitive intervention, particularly for individuals with ADHD or other cognitive impairments. Additionally, incorporating neuroimaging techniques such as EEG or fMRI could provide deeper insights into the neural mechanisms underlying binaural beat effects. Overall, this study offers evidence supporting the cognitive benefits of 40 Hz binaural beats, but further research is necessary to elucidate the mechanisms underlying this effect.

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