Journal of Neurodevelopmental Cognition

Journal of Neurodevelopmental Cognition 6(4) (2025) 1- 30 10.48308/jncog.2026.245084.1044
ISSN: 2645-565X
http://www.jncog.sbu.ac.ir

Binaural Beats and Cognitive-Neural Outcomes: A Scoping Review

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Abstract

Objective: Binaural beats are an auditory illusion produced when two tones with slightly different frequencies are presented separately to each ear, generating the perception of a third tone equal to the frequency difference. They have been investigated as a non-invasive approach for modulating neural activity and influencing cognitive and behavioural processes, although reported findings remain inconsistent. This scoping review mapped empirical evidence published between 2005 and 2025 on the neurophysiological mechanisms of binaural beats and their reported neural, cognitive, and behavioural outcomes.

Method: Following PRISMA-ScR guidelines, systematic searches were conducted in PubMed, Scopus, Web of Science, and PsycINFO. Human empirical studies using binaural beat stimulation and reporting electrophysiological, neuroimaging, or behavioural outcomes were included. Twenty-five studies involving 432 participants met the eligibility criteria.

Results: Reported findings varied considerably across studies, with some demonstrating significant neural or behavioural effects and others reporting null or mixed results. Positive findings were more frequently reported in studies investigating theta- and gamma-frequency stimulation; however, substantial heterogeneity in participant characteristics, stimulation protocols, outcome measures, and study designs precluded conclusions regarding comparative effectiveness or optimal stimulation parameters.

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Received: August 2025 *Accept: November 2025*

Discussions: Current evidence suggests that binaural beats may influence neural dynamics, but methodological heterogeneity and inconsistent reporting limit firm conclusions. Future research should adopt standardized protocols, adequately powered study designs, and integrated neural and behavioural outcome measures to improve reproducibility and clarify the effects of binaural beat stimulation.

Keywords*:* Auditory Illusion, Cognitive functions, Cognitive Rehabilitation, Neural entrainment, Neural oscillations

1. Introduction

Binaural beats are defined as a perceptual auditory illusion that occurs when two tones of slightly different frequencies are presented separately to the left and right ears; the brain then perceives a third tone corresponding to the frequency difference between the two inputs, even though that tone is not physically present (e.g., a 310 Hz tone in one ear and a 320 Hz tone in the other produces a 10 Hz binaural beat). This phenomenon differs from monaural beats, in which the two frequencies are combined before reaching the ears (both ears receive the same combined signal), creating physical amplitude modulation rather than central perceptual generation; binaural beats, by contrast, arise purely from neural processing, primarily within the brainstem's superior olivary complex (Aparecido-Kanzler, Cidral-Filho, & Prediger, 2021; Ingendoh, Posny, & Heine, 2023).

Binaural beats have gained increasing interest as a potential noninvasive tool for entraining brainwave frequencies, based on the brainwave entrainment hypothesis, which proposes that exposure to auditory stimuli at specific frequencies can drive the brain's electrophysiological activity to synchronize with the external rhythm, thereby potentially modulating cognitive and affective states (Ingendoh et al., 2023). The literature has investigated effects on various psychological domains, including attention, memory, mood, pain perception, relaxation, creativity, and emotional states (Askarpour, Mirzaee, Habibi, & Pourfridoni, 2024). Meanwhile, reviews in the literature emphasize mixed outcomes and methodological variability across EEG studies, while highlighting the theoretical role of binaural beats in neuroscience and psychological research (Ingendoh et al., 2023). Other reviews emphasize potential benefits in domains such as memory, mood disorders (e.g., anxiety, depression), and sleep quality; however, they also underscore the inconsistency of existing findings and the necessity for further rigorous investigation (Mallik & Russo, 2022).

This scoping review maps the literature on binaural beats to identify key concepts, mechanisms, neuroscientific and cognitive associations, methodological approaches, and potential applications. It distinguishes binaural beats from other auditory phenomena, such as monaural beats, and traces the early scientific developments in the field. Methodological heterogeneity is also addressed, considering variations in experimental design, stimulation parameters, EEG measurement techniques, and control conditions that may contribute to inconsistent findings. Furthermore, the review explores the translational relevance of binaural beats, mapping their potential for cognitive enhancement, mental health, and sleep regulation, while identifying gaps and suggesting directions for future research. By charting key themes, evidence types, and gaps, this review provides an overview of the literature base. It outlines a roadmap for interdisciplinary research in neuroscience and cognitive science.

1. Comparisons Across Frequency Bands

Evidence comparing binaural beat effects across frequency bands remains inconsistent, reflecting fundamental uncertainties regarding whether entrainment is frequency-specific. Although several studies report entrainment in lower (delta, theta) and higher (gamma) bands, findings in the alpha and beta ranges are markedly less reliable. For example, the review by Ingendoh et al. (2023) identified entrainment in delta, theta, and gamma frequencies but found no consistent evidence for beta-band effects, with alpha studies producing similarly mixed outcomes. (Ingendoh et al., 2023).

Other reviews, such as Mirmohamadi et al. (2024), likewise noted that while low-frequency entrainment appears more robust, higher frequencies may exceed the phase-locking capacities of cortical populations, contributing to the observed variability. (Mirmohamadi, Norozpour, & Zarrabian, 2024).

Parametric investigations provide additional nuance. Melnichuk et al. (2025) demonstrated that gamma-band stimulation, when optimized through specific carrier tones and masking noise, produced stronger neural alignment and measurable cognitive benefits, whereas beta-band stimulation did not reliably do so. Such findings suggest that frequency-dependent effects may arise not only from neurophysiological constraints but also from the interaction of stimulation parameters with neural dynamics. (Melnichuk, Cooper Jr, & Hawk Jr, 2025).

Despite these individual insights, the broader literature remains methodologically heterogeneous, with substantial variation in stimulation protocols, analytic strategies, and participant characteristics. As a result, cross-study comparisons are limited, and no definitive frequency-response profile has been established. Addressing this gap will require standardized definitions of entrainment, harmonized EEG analysis pipelines, and experimental designs that systematically manipulate frequency while controlling for confounding stimulus features. Such methodological refinement is essential for clarifying whether binaural beat effects are genuinely frequency-specific or primarily driven by protocol-dependent factors.

2. Stimulation Protocols and Optimization

This section outlines the methodologies employed in binaural beat research, with an emphasis on experimental parameters, exposure duration, delivery methods (e.g., headphones versus free-field presentation), distinctions between acute and long-term protocols, population-specific considerations, and the critical need for standardized practices.

3. Overview of Experimental Protocols

Binaural beats have been applied across a wide range of EEG frequency bands, typically encompassing delta (0.5–4 Hz), theta (4–8 Hz), alpha (8–13 Hz), beta (13–30 Hz), and gamma (>30 Hz) ranges. Delta-band binaural beat has been investigated for deep sleep and restorative states, whereas theta-band binaural beat is associated with meditation and creative processes. Alpha binaural beat is commonly employed for relaxation, beta binaural beat for alertness, and gamma binaural beat for higher-order cognitive functions (Askarpour et al., 2024).

4. Duration of exposure:

Short-term binaural beat protocols typically consist of listening sessions lasting 5–30 minutes. Studies have shown that daily exposure to 6 Hz binaural beat for 10 minutes over two weeks enhances cognitive processing, as evidenced by increased P300 amplitude and reduced latency in EEG measures. These effects are further strengthened with continued exposure over one month. Practice and familiarity appear to amplify neural entrainment effects over time (Chockboondee, Jatupornpoonsub, Lertsukprasert, & Wongsawat, 2024).

5. Sound intensity and equipment (headphones vs. free field):

The perception of binaural beats requires the presentation of two slightly different frequencies to each ear independently; therefore, the use of stereo headphones is indispensable for preserving the auditory illusion. Free-field or speakers fail to preserve interaural separation and can disrupt perceptual integrity (Le Scouranec, Poirier, Owens, & Gauthier, 2001).

6. Acute vs. Long-Term Protocols

Acute binaural beat protocols typically comprise single sessions lasting from a few minutes to approximately 30 minutes and are commonly employed to assess immediate electrophysiological or behavioral responses. In contrast, evidence indicates that long-term protocols, which involve repeated daily exposure over several weeks, may produce more robust and sustained effects. For instance, the aforementioned 6 Hz binaural beat study reported cumulative enhancement in auditory ERP indices following one month of daily stimulation (Chockboondee et al., 2024).

7. Population-Specific Parameters

Healthy adults vs. clinical populations:

Most existing studies have focused on healthy young adult samples. Recent advances highlight the potential of personalized binaural beats protocols, wherein beat frequencies are adjusted according to an individual's heart-rate-derived resonance. Notably, Corona-González et al. (2021) implemented personalized theta- and beta-range binaural beat stimulation and assessed EEG power dynamics in a cohort of 20 healthy volunteers using a 20-minute stimulation paradigm with a resting control condition (Corona-González, Alonso-Valerdi, & Ibarra-Zarate, 2021).

Research involving clinical and special populations remains markedly limited. Existing literature reviews suggest potential benefits for domains such as memory, mood disorders, sleep quality, and neurological conditions, including ADHD; however, current findings are inconsistent and underscore the need for rigorously designed, population-specific investigations (Askarpour et al., 2024).

8. Toward Standardized Protocols

A variability in the literature in binaural beat research lies in substantial methodological heterogeneity across studies, which compromises both comparability and reproducibility. In a systematic review of 14 EEG investigations, Ingendoh et al. (2023) documented considerable variability in beat frequencies, carrier tones, stimulation durations, control conditions, and analytic approaches. This heterogeneity contributed to inconsistent findings, with five studies reporting entrainment effects, eight yielding null results, and one presenting mixed outcome (Ingendoh et al., 2023). The authors emphasize the critical need for standardized protocols to ensure methodological consistency in future studies. Meta-analytic evidence from broader behavioral outcomes suggests that masking binaural beat with white or pink noise does not significantly impact effectiveness, which may simplify protocol design (Garcia-Argibay, Santed-Germán, & Reales, 2019). Meanwhile, some experimental studies (e.g., Melnichuk et al., 2025) adopt parametric designs varying beat frequency, carrier tone, and background noise to isolate optimal combinations for sustained attention and entrainment (Klichowski, Wicher, Kruszwicka, & Golebiewski, 2023; Melnichuk et al., 2025).

In summary, current evidence underscores several key considerations in the application of binaural beat stimulation. Frequency selection typically ranges from delta to gamma bands, with each frequency domain associated with distinct cognitive or affective processes. Exposure duration emerges as another critical factor: while short-term sessions may be sufficient to induce acute effects, sustained or repeated stimulation appears necessary to consolidate neural and behavioral outcomes. The mode of delivery is also essential, as headphone-based presentation is required to preserve the binaural illusion, whereas free-field delivery fails to achieve the same effect. Increasing attention has been directed toward personalized approaches, such as heart-rate-based frequency tuning, which hold promise but remain underexplored in clinical contexts. Across these domains, however, the field continues to be constrained by methodological heterogeneity, underscoring the necessary need for standardized protocols to reconcile inconsistent findings and enable more rigorous translation into applied and clinical settings.

9. Cognitive Effects of Binaural Beats

Binaural beats have been investigated for their potential to modulate a range of cognitive domains, including attention, working memory, and executive control. This section maps the current literature, delineating both the observed benefits and the variability across studies.

Attention and Alertness

Accumulating evidence indicates that high-frequency binaural beats, particularly within the gamma band (30–100 Hz), may facilitate attentional engagement and alertness. For instance, exposure to approximately 40 Hz stimulation has been shown to improve reading comprehension accuracy and attenuate interference effects in global–local attention paradigms, suggesting a narrowed attentional scope and enhanced selective processing (Zhao & Van Hedger, 2025).

A meta-analysis of research on binaural beats effects concluded that exposure to binaural beats is associated with improvements in attention and memory, with longer listening durations (≥10 minutes) yielding stronger effects (Garcia-Argibay et al., 2019). Despite these positive findings, the overall evidence base remains mixed, partly due to variations in frequencies, exposure durations, and outcome measures.

Memory Enhancement

Working memory capacity (WMC) has been a central target in binaural beats research. Kraus and Porubanová (2015) examined the impact of alpha-range binaural beats (7.5–12.5 Hz) on WMC using the operation span (OSPAN) task. Participants exposed to alpha-frequency stimulation exhibited significantly greater WMC compared to controls who listened to ambient sea sounds, indicating that alpha-band binaural beat may enhance cognitive mechanisms underlying memory maintenance and attentional control (Beauchene, Abaid, Moran, Diana, & Leonessa, 2016; Kraus & Porubanová, 2015).

Additional evidence from systematic reviews suggests that binaural beat stimulation in the beta and gamma frequency ranges may facilitate both working and long-term memory performance; however, results remain inconsistent across studies (Askarpour et al., 2024; Brown, 2025).

Executive Functions

Hommel (2016) reported enhancements in cognitive flexibility, a core executive function, following exposure to high-frequency binaural beats. These findings are consistent with theoretical perspectives suggesting that gamma-band stimulation may support integrative mechanisms of cognitive control (Hommel, Sellaro, Fischer, Borg, & Colzato, 2016).

An event-related potential (ERP) study examined the effects of a single 20-minute session of beta-frequency binaural beats (25 Hz) on executive functioning in healthy adults. Following stimulation, participants performed a Stroop task, with both behavioral measures (accuracy and reaction time) and neural indices (P300 and N400 components) recorded. The findings suggest that beta-band binaural beat may transiently modulate executive control, although detailed results were not fully reported (Mahajan et al., 2021).

In summary, the literature indicates that binaural beats, particularly within the beta and gamma frequency ranges, may enhance attention, working memory, and executive functions under specific conditions. Nevertheless, substantial methodological heterogeneity, including variability in frequency selection, exposure duration, cognitive task paradigms, and EEG measures, limits the generalizability and conclusiveness of these findings. Furthermore, some studies report inconsistent or even adverse effects on memory and cognitive performance under certain conditions, such as brief exposure durations or lower-frequency stimulation (Askar pour et al., 2024).

Future research should employ rigorous, well-calibrated study designs, ideally incorporating sham-controlled protocols, standardized cognitive tasks, and neurophysiological measures (e.g., EEG or fMRI), alongside longitudinal assessments. Such approaches are essential to validate the cognitive enhancement potential of binaural beats and to identify optimal stimulation parameters.

Taken together, the characteristics of the included studies demonstrated substantial heterogeneity in terms of participant populations, stimulation protocols, outcome measures, and methodological approaches. Most studies (n=23) were conducted with healthy young adults, with ages ranging between 18 and 35 years. Some studies (n=2) included clinical populations. Sample sizes varied widely, from pilot studies with as few as 13 participants to larger trials involving more than 50 participants. The cultural and geographical distribution of the studies was broad, with research groups based in North America, Europe, Asia, and South America.

In terms of stimulation design, the majority of studies implemented binaural beats in the theta (4–8 Hz), alpha (8–12 Hz), and beta (12–20 Hz) ranges, though a substantial subset investigated gamma-frequency beats (>30 Hz). Delta frequencies were less commonly studied. Carrier tones typically ranged from 100 to 500 Hz, with 250 Hz being the most frequently chosen frequency. Exposure durations ranged from as little as 3 minutes to as long as 33 minutes, with 15–20 minutes being the modal value. Most studies employed continuous presentation of binaural beats, though a few adopted designs with alternating periods of stimulation and silence. Control conditions included pure tones, monaural beats, white or pink noise, and, in some cases, silence.

2. Method

Eligibility Criteria

Studies were included if they were quasi-experimental or experimental investigations examining the effects of binaural beats on brain activity (e.g., EEG measures), cognitive outcomes (e.g., memory, attention, cognitive flexibility), or psychological states (e.g., anxiety, mood) in human participants. There were no restrictions on participants' age, health status, or language of publication. Studies had to report empirical data from interventions involving binaural beats at any frequency (e.g., alpha, beta, theta, gamma). Exclusion criteria were: animal studies, non-empirical publications (e.g., commentaries), studies not involving binaural beat stimulation, or studies focusing solely on monaural beats or unrelated auditory stimuli.

Information Sources

A comprehensive search was conducted across multiple electronic databases, including PubMed/MEDLINE, Scopus, Web of Science, IEEE Xplore, and Google Scholar, to capture biomedical, psychological, and neuroscience literature. Grey literature was searched via ProQuest Dissertations and Theses Global and relevant conference proceedings. Clinical trial registries (e.g., ClinicalTrials.gov) were examined for ongoing or unpublished studies. Searches were limited to publications from 2005 to 2025, with no initial language restrictions.

Search Strategy

The search strategy was developed iteratively in consultation with a research librarian. It was tailored to each database using a combination of controlled vocabulary (e.g., MeSH terms in PubMed such as "Electroencephalography," "Cognition," and "Auditory Perception") and free-text keywords. Key search terms included variations of "binaural beats," "binaural beat stimulation," "auditory beats," "brain entrainment," "EEG," "brainwave modulation," "cortical connectivity," "cognitive enhancement," "memory performance," "attention," "anxiety," "stress mitigation," and "mood." Boolean operators were used to combine terms (e.g., "binaural beats" AND (EEG OR "brain activity" OR cognition OR anxiety OR memory)). Filters were applied for human studies and publication dates from 2005 onward. An example PubMed search string was: ("binaural beats"[Title/Abstract] OR "auditory beat stimulation"[Title/Abstract]) AND (EEG[Title/Abstract] OR "brain entrainment"[Title/Abstract] OR cognition [Title/Abstract] OR anxiety [Title/Abstract] OR memory [Title/Abstract]) AND ("2005/01/01"[Date - Publication]: "2025/09/30"[Date - Publication]). The strategy was piloted and refined to ensure sensitivity and specificity, with reference lists of included studies hand-searched for additional relevant articles.

Selection Process

After duplicate removal using EndNote software, two reviewers independently screened titles and abstracts against the eligibility criteria. Full-text articles of potentially eligible studies were retrieved and assessed independently by the two reviewers. Disagreements were resolved through discussion or consultation with a third reviewer. The study selection process followed PRISMA-ScR guidelines, resulting in 25 studies included in the final review.

Data Charting Process

A standardized data charting form in Microsoft Excel was developed and piloted on five studies to ensure consistency and comprehensiveness. Two reviewers independently extracted data from each study, with discrepancies resolved through consensus discussions. The charting form captured elements aligned with the review objectives, including study characteristics, participant details, intervention parameters, outcomes, and reported findings.

Data Items

Extracted data included: (1) study identification (authors, year, title, journal); (2) study design (e.g., quasi-experimental, pre-post, controlled); (3) participant characteristics (sample size, age, gender, health status); (4) intervention details (binaural beat frequency, duration, delivery method, control/comparison conditions); (5) outcome measures (primary: EEG metrics such as spectral density, power changes, connectivity; secondary: cognitive assessments for memory, attention, flexibility; psychological measures for anxiety, mood, and stress); (6) key findings; and (7) limitations or potential sources of bias.

Synthesis Approach

For descriptive evidence mapping, studies were categorized according to the primary conclusions reported by the original authors. "Positive findings" referred to studies reporting statistically significant neural, behavioral, or cognitive effects attributed to binaural beat stimulation. "No effect" referred to studies reporting no statistically significant differences between intervention and control conditions for the primary outcomes. "Mixed findings" referred to studies reporting significant effects only for selected outcomes, participant subgroups, stimulation conditions, or frequency bands, while other outcomes remained non-significant. These categories were used solely for descriptive mapping and should not be interpreted as indicators of intervention effectiveness or evidence strength.

Given heterogeneity in study designs, intervention parameters, and outcomes, results were synthesized descriptively. Findings were grouped thematically into four categories: (1) EEG and brain activity changes; (2) cognitive effects; (3) psychological effects; and (4) null or inconsistent outcomes. Patterns were qualitatively summarized, and data were tabulated to highlight key associations, such as frequency-specific effects. Evidence gaps and variability in outcomes across studies were also identified.

Inter-Rater Reliability

To ensure reliability in screening and data extraction, two reviewers independently performed all tasks, with discrepancies resolved by discussion or consultation with a third reviewer. Agreement rates were documented during the pilot and full extraction phases, demonstrating a high level of inter-rater reliability and enhancing the reproducibility of the review process.

Methodological Characteristics of the Included Studies

Consistent with PRISMA-ScR recommendations, no formal critical appraisal or structured risk-of-bias assessment was conducted because the primary objective of this scoping review was to map the breadth and characteristics of the available literature rather than evaluate intervention effectiveness. Nevertheless, several methodological characteristics were descriptively documented during data charting to provide contextual information about the existing evidence base. These observations are intended solely to describe common methodological features of the included studies and should not be interpreted as formal assessments of study quality or certainty of evidence.

Most studies were small-scale exploratory designs with sample sizes below 40 participants, and only about 20% applied random assignment or counterbalancing to control for order effects (Askarpour et al., 2024; Ingendoh et al., 2023). Blinding procedures were rarely implemented: in the majority of EEG and behavioral experiments, participants were aware of the stimulation condition, and experimenters were not blinded during data collection, increasing susceptibility to expectancy effects (Mallik & Russo, 2022; Perez, Dumas, & Lehmann, 2020). Only a few studies employed single- or double-blind protocols (Padmanabhan, Hildreth, & Laws, 2005) (Kraus & Porubanová, 2015), and none reported allocation concealment.

Reporting transparency was also variable. Several investigations did not disclose the exact sound intensity (dB SPL) or technical details of the auditory equipment, such as headphone model, frequency response, or calibration method, parameters that critically influence perceptual and neural outcomes (Borges, Arantes, & Naves, 2023; Le Scouranec et al., 2001). Similarly, only five studies reported a priori power analyses or effect size estimates, reducing the statistical reliability of their conclusions. The possibility that unpublished studies with null findings exist cannot be ruled out; however, publication bias was not formally assessed in this scoping review.

Taken together, these observations suggest that much of the existing binaural beat literature should be interpreted as preliminary or proof-of-concept evidence rather than confirmatory. To strengthen methodological integrity in future research, studies should employ larger, statistically powered samples, adopt pre-registered and randomized double-blind designs, and provide comprehensive methodological documentation, including headphone calibration, auditory intensity, randomization methods, and blinding procedures. Future experimental studies should adopt established reporting guidelines appropriate to their study design (e.g., CONSORT for randomized trials) and provide comprehensive methodological documentation to facilitate reproducibility and evidence synthesis.

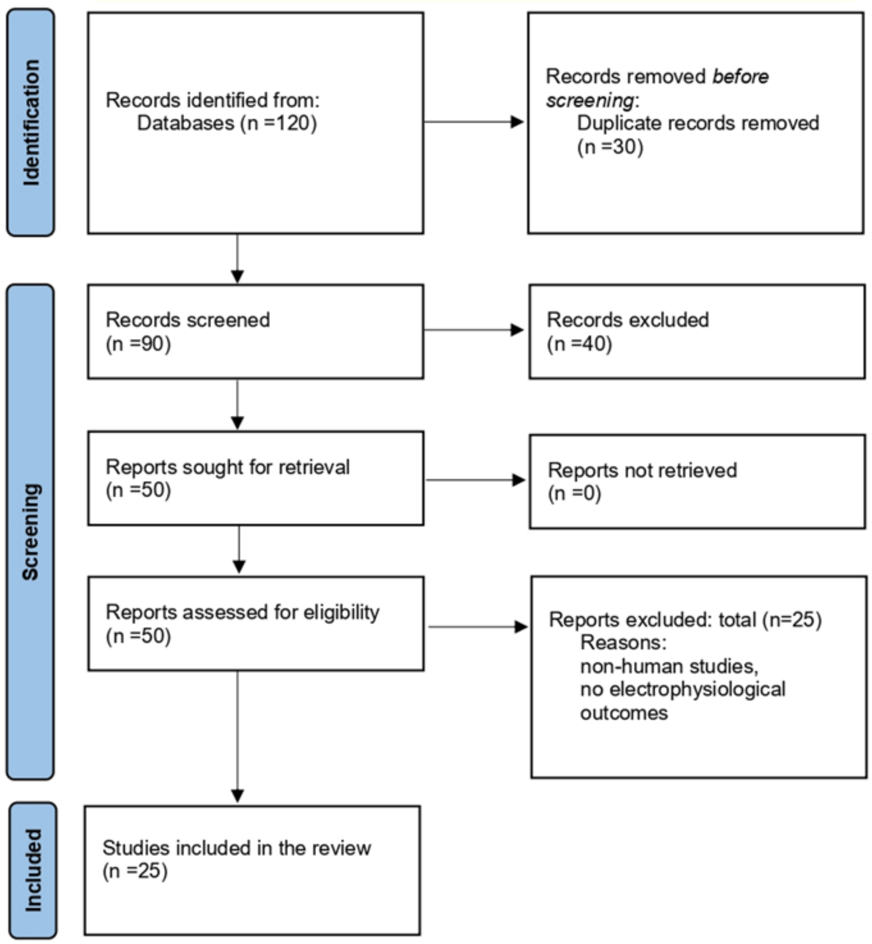

Figure 1: *Flow chart for search process. This flow chart illustrates the study selection process for our scoping review, detailing the identification, screening, and inclusion of studies from databases, following PRISMA-ScR guidelines*.

3. Results

The systematic search across four electronic databases yielded a total of 120 records. After removing 30 duplicates, 90 records were subjected to title and abstract screening. At this stage, 40 records were excluded because they were unrelated to binaural beats, focusing instead on monaural beats, music therapy, or general auditory processing. Fifty full-text articles were retrieved for further evaluation. Of these, 10 were excluded because they either did not provide a clear binaural beat protocol, combined binaural beats with other interventions, or failed to report outcomes relevant to cognition, language, or neurophysiology. The remaining 25 studies met the inclusion criteria and were included in the descriptive synthesis.

Electrophysiological findings were mixed. While several studies, particularly those using theta and gamma frequencies, reported evidence of entrainment or modulation of ASSRs and FFRs, an equivalent number found no measurable neural synchronization, consistent with earlier reviews noting substantial variability in entrainment robustness. Studies investigating functional connectivity suggested that binaural beats may influence network organization, yet these effects were inconsistent and often limited to specific tasks or fatigue contexts.

Behavioral outcomes were varied. Studies in the beta range frequently described associations with working memory and attentional performance, aligning with beta oscillations and cognitive engagement. Theta stimulation was often linked to relaxation and learning, while gamma stimulation was associated with cognitive flexibility and phonological processing. However, not all studies replicated these associations. Some reported null results, particularly for alpha-frequency beats, which were explored for relaxation but often showed limited associations. Clinical studies were limited by small sample sizes, short intervention periods, and a lack of long-term follow-up.

Overall, the data charting suggests a range of potential associations for binaural beats in modulating brain function, with heterogeneity in protocols and outcomes. The most commonly explored effects were in theta and gamma frequencies, while alpha and beta outcomes were more variable. Methodological diversity, including differences in stimulation protocols, EEG analytic techniques, and control conditions, contributes to this variability.

To summarize, the scoping review identified 25 studies that examined binaural beat stimulation in relation to neural oscillations and cognitive processes. Approximately 40% of these studies described findings aligned with brainwave entrainment, while the remainder reported null or mixed outcomes. The results map the potential of binaural beats as a non-invasive tool for cognitive exploration, as well as areas for further methodological standardization and large-scale studies.

Evidence Mapping

Outcome Domain	Delta	Theta	Alpha	Beta	Gamma
Neural entrainment	2	5	1	1	8
EEG spectral changes	1	4	3	2	3
Functional connectivity	0	2	1	3	4
Working memory	0	3	2	2	2
Attention	0	3	1	2	4
Executive function	0	1	1	2	3
Memory	0	2	1	1	2
Anxiety / stress	2	3	1	1	1
Learning & reading	0	1	0	0	2
Sleep and relaxation	2	2	1	0	0
Behavioral performance	0	2	1	1	1
Adverse effects	0	0	1	1	1

0	1	2	3	4	5	6	7	8	9	10

Figure 2. *Evidence map summarizing the distribution of studies investigating the effects of binaural beats across EEG frequency bands (delta, theta, alpha, beta, and gamma) and cognitive–neural outcome domains. Cell values represent the number of studies reporting each outcome–frequency band of binaural beat association. Colour intensity reflects the relative concentration of evidence, with red to green tones indicating lower to higher evidence density. This figure illustrates the distribution of published studies across stimulation frequencies and outcome domains. It does not represent effect sizes, study quality, certainty of evidence, or comparative effectiveness of binaural beat stimulation.*

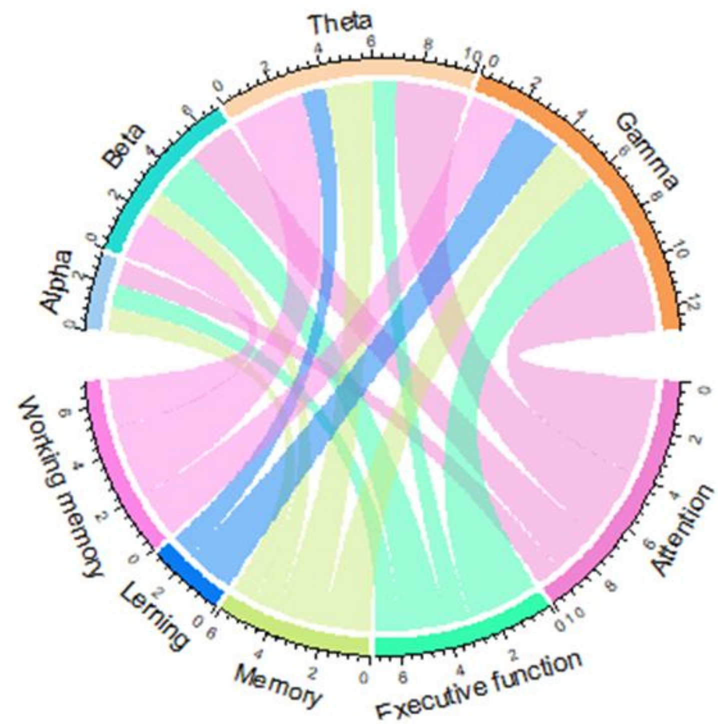

Figure 3. *Chord diagram showing the distribution of evidence linking binaural beat frequency bands to cognitive outcomes. This chord diagram summarizes the number of published studies reporting an association between specific binaural beat frequency bands (Alpha, Beta, Theta, and Gamma) and cognitive–neural outcomes. The upside of the diagram represents binaural beat frequency bands, while the bottom side represents cognitive domains, including Attention, Executive Function, Memory, Learning, and Working Memory. Each chord connecting a frequency band to a cognitive domain indicates that at least one study reported a relevant correlation or effect. The width of each chord is proportional to the number of studies supporting that association, thereby reflecting the relative strength of evidence in the literature rather than effect size. Coloured segments along the outer circle denote the total number of studies associated with each frequency band and cognitive domain. The Delta binaural beat frequency band is not included in the diagram because no eligible studies were identified that demonstrated its effectiveness in improving cognitive performance. Overall, the diagram provides an integrative visual overview of how empirical evidence is distributed across frequency bands and cognitive outcomes in the current body of research on binaural beats. The chord widths reflect only the number of published studies reporting each frequency–outcome association. They should not be interpreted as indicators of intervention effectiveness, strength of association, or certainty of evidence*.

Ethical and Safety Considerations

Despite the potential benefits, ethical and safety considerations are paramount. Binaural beats are generally considered safe in healthy populations, with minimal adverse effects reported (Padmanabhan et al., 2005). However, careful screening is recommended for individuals with epilepsy, severe psychiatric disorders, or auditory hypersensitivity, since high-frequency binaural beats may provoke seizures or discomfort in vulnerable populations. Ethical application requires informed consent, transparent disclosure of expected outcomes, and caution against overstating therapeutic effects. Practitioners should integrate binaural beat as an adjunct to, rather than a substitute for, established interventions, thereby ensuring adherence to evidence-based practice.

4. Discussion

Consistent with PRISMA-ScR recommendations, no formal critical appraisal or structured risk-of-bias assessment was performed because the primary objective of this review was to map the available evidence rather than evaluate intervention effectiveness. Therefore, observations regarding methodological limitations should be interpreted as descriptive characteristics of the included literature rather than formal assessments of study quality.

The evidence based on binaural beats research shows substantial heterogeneity in study design, stimulation parameters, participant characteristics, analytical approaches, and outcome measures. This variability, while reflecting the exploratory nature of the field, limits the comparability and reproducibility of results. Addressing these inconsistencies is essential for refining theoretical models and guiding the next generation of experimental and clinical studies. The following sections delineate the principal sources of heterogeneity and provide specific methodological recommendations to address each.

1. Integrative Synthesis

Physiologically, binaural beats arise from interaural frequency differences that are initially processed in the cochlea and subsequently integrated within brainstem nuclei, particularly the superior olivary complex. This process gives rise to frequency-following responses detectable with EEG and MEG (Karino et al., 2006; Perez et al., 2020). At the neurobiological level, binaural beats have been proposed to engage distributed cortical and subcortical networks, including thalamocortical loops and limbic structures implicated in attention, arousal, and emotional regulation (Hommel et al., 2016; Vernon, Peryer, Louch, & Shaw, 2014). Electrophysiological studies further indicate that binaural beats can elicit steady-state auditory-evoked potentials (SSAEPs) and modulate functional connectivity across cortical regions, although findings vary across frequency bands and individuals (Ingendoh et al., 2023; Mirmohamadi et al., 2024).

At the cognitive level, higher-frequency stimulation (beta/gamma) has been more frequently associated with attention, working memory, and executive functions, whereas lower-frequency stimulation (delta/theta) is commonly linked to relaxation and stress reduction (Padmanabhan et al., 2005; Zhao & Van Hedger, 2025).

2. Comparison Across Studies

Across studies, considerable variability is evident in both neural and behavioural outcomes. Some EEG investigations report robust neural entrainment effects (Mirmohamadi et al., 2024; Perez et al., 2020), whereas others observe limited or absent modulation of oscillatory activity (Ingendoh et al., 2023; López-Caballero & Escera, 2017). Similarly, Behavioural findings show a similar pattern; improvements in attention or working memory have been reported in certain populations (Kraus & Porubanová, 2015; Zhao & Van Hedger, 2025) but these effects are not consistently replicated across protocols, durations, or age groups.

These variations may reflect differences in stimulus parameters (carrier tone, frequency, duration), participant characteristics, EEG measurement techniques, and task selection. In particular, the interaction between binaural beat frequency and specific cognitive or linguistic domains remains insufficiently mapped and warrants further systematic investigation.

3. Strengths, Limitations, and Methodological Challenges

The literature's multi-modal approach, integrating behavioural, electrophysiological, and neuroimaging data, allows for a broad overview of binaural beat mechanisms and applications. Emerging descriptions in clinical populations extend relevance beyond healthy adults.

However, gaps include small sample sizes, variability in protocols (e.g., frequency selection, stimulus duration, headphone calibration), and limited longitudinal follow-ups, which restrict understanding of sustained effects. Most studies focus on short-term interventions, leaving long-term utility underexplored.

A quantitative overview of the 25 included studies highlights systematic rather than random variability. Ten studies (40%) reported clear neural entrainment or behavioural enhancement, eleven (44%) found no significant effects, and four (16%) yielded mixed or frequency-dependent outcomes (Ingendoh et al., 2023). These inconsistencies appear closely linked to several methodological dimensions.

Stimulation duration is a key factor. Studies employing short time of exposures (<10 minutes), such as Vernon et al. (2014) and López-Caballero & Escera (2017), were less likely to demonstrate entrainment or behavioural effects. In contrast, longer or repeated sessions (≥20 minutes), including those by Chockboondee et al. (2024) and Kraus & Porubanová (2015), more consistently reported enhanced EEG synchronization, increased ERP amplitudes, or improved task performance.

The frequency band of the binaural beat also contributed to outcome variability. Among the previous studies, theta stimulation showed the highest proportion of positive entrainment effects (67%), followed by gamma (60%), whereas alpha (33%) and beta (20%) stimulation yielded more inconsistent results (Melnichuk et al., 2025; Wang et al., 2022). This pattern aligns with physiological evidence suggesting that lower-frequency stimulation has been hypothesized that engages thalamocortical circuits linked to relaxation and memory, while higher-frequency stimulation modulates cortical synchronization associated with attention and executive control. Differences in carrier tones (100–500 Hz) and modulation depth further complicate interpretation, as lower carrier tones enhance phase-locking and perceptual strength, whereas higher tones often diminish entrainment effects (Hommel et al., 2016; Jirakittayakorn & Wongsawat, 2017).

Auditory context further influenced outcomes. Studies that masked binaural beats with white or pink noise (n = 6) or embedded them in musical backgrounds (n = 3) generally reported attenuated entrainment magnitudes or non-significant behavioural effects (Borges et al., 2023; Mallik & Russo, 2022). In contrast, those using pure binaural beat stimulation via calibrated headphones (n = 16), for example, Perez et al. (2020) and Wang et al. (2022), were more likely to detect statistically significant neural and behavioural modulation (Perez et al., 2020; Wang et al., 2022). These findings suggest that background masking, although sometimes employed to enhance comfort, may actually interfere with phase locking and neural coherence.

Most binaural beat studies recruit healthy young adults, resulting in limited generalizability across age groups, clinical conditions, and neurodiverse populations. The vast majority of studies (n = 23) were conducted on healthy young adults (aged 18–35), while only two included clinical populations (e.g., individuals with anxiety). Interestingly, both clinical studies reported moderate-to-strong effects on anxiety reduction (Padmanabhan et al., 2005; Power, Mead, Barnes, & Goswami, 2013), suggesting that clinical populations might exhibit higher sensitivity to binaural beat stimulation, possibly due to altered baseline oscillatory activity. Furthermore, confounding factors such as chronotype, emotional state, and hearing thresholds are rarely measured or statistically controlled. Without such covariates, distinguishing genuine entrainment effects from baseline variability becomes challenging.

4. Task and outcome variability

Behavioural and cognitive assessments in binaural beat research vary substantially in nature and complexity. Attention, working memory, executive control, and relaxation have all been investigated using distinct tasks such as Stroop, Flanker, and N-back paradigms (Mahajan et al., 2021) In linguistic studies, tasks range from phoneme discrimination to reading comprehension (Zhao & Van Hedger, 2025) Such task heterogeneity obscures direct cross-study comparison and complicates the interpretation of cognitive specificity.

Standardized task batteries should be developed for major cognitive domains, ensuring psychometric equivalence across studies. Combined behavioral–neurophysiological paradigms (e.g., simultaneous EEG recording during task performance) should be employed to link entrainment metrics directly to cognitive outcomes. Researchers should also report effect sizes and reliability indices to facilitate meta-analytic synthesis.

5. Measurement and analytical inconsistencies

EEG and neuroimaging methodologies display notable variability in data acquisition and analysis pipelines. Differences in electrode configurations, referencing schemes, artifact correction, and frequency filtering can produce divergent outcomes (Ingendoh et al., 2023). Moreover, definitions of entrainment vary: some operationalize it as increased spectral power at the beat frequency, others require phase synchronization or cross-frequency coupling (Perez et al., 2020; Wang et al., 2022).

Few studies integrate multimodal imaging, and most rely on small-sample EEG designs. Neuroimaging investigations using fMRI or MEG remain exploratory (Abd Hamid et al., 2025), limiting spatial and network-level understanding.

Consensus criteria for defining neural entrainment should be established. Standardized EEG analysis protocols, including spectral decomposition ranges, coherence metrics, and cross-frequency coupling indices, should be published as open methodological frameworks. Incorporating multimodal designs (EEG-fMRI or MEG connectivity) will enhance spatial precision and permit cross-validation of entrainment phenomena.

6. Reporting quality and reproducibility

The literature shows inconsistent reporting of essential methodological details such as sound intensity, headphone model, calibration, and participant blinding. Inadequate transparency limits reproducibility and may partially explain mixed findings (Ingendoh et al., 2023). Moreover, many studies employ custom or proprietary binaural beat-generation software without sharing stimulus code, which hampers replication efforts.

7. Temporal and contextual confounds

Temporal factors such as time of day, fatigue level, and environmental noise are rarely controlled despite their known effects on neural oscillations and attentional capacity (Wang et al., 2022). Similarly, laboratory settings differ in ambient lighting and soundproofing, potentially influencing mood and arousal during stimulation. These uncontrolled contextual variables introduce noise into both neural and behavioural measurements.

Future studies should record contextual parameters and, where possible, standardize environmental conditions. Randomizing session times and counterbalancing testing orders can minimize circadian and fatigue effects. Employing within-subject designs with repeated measures will further reduce inter-session variability.

Taken together, the current literature suggests that stimulation frequency, exposure duration, participant characteristics, and experimental methodology may all contribute to variability across reported findings. Therefore, no definitive conclusions regarding optimal stimulation protocols can be drawn from the current evidence base.

Future studies could standardize experimental protocols, including consistent carrier tones, beat frequencies, exposure durations, and control conditions. Longitudinal designs would help map the persistence of effects. Integration with neuroimaging methods, such as fMRI and MEG, may clarify network-level mechanisms and individual variability. Expanded research in clinical and neurodevelopmental populations could further map therapeutic applications, particularly in language rehabilitation, ADHD, dyslexia, and stuttering. Exploring personalized binaural beat protocols, based on baseline neural oscillatory profiles, could optimize approaches and translation to educational or clinical settings. Interdisciplinary collaboration between neuroscientists, psychologists, engineers, and clinicians will also be essential for translating binaural beat findings into practical cognitive and therapeutic applications.

5. Conclusion

Binaural beats represent a non-invasive and low-cost approach explored in relation to modulating neural oscillations and cognitive performance. The literature describes binaural beat engaging cortical and subcortical networks through the auditory pathway, with associations to attention, arousal, and emotional states. Future research should focus on standardizing protocols, conducting longitudinal assessments, implementing personalized frequency targeting, and integrating binaural beat into multimodal rehabilitation and educational frameworks. In summary, while methodological variability currently limits definitive conclusions, the accumulating evidence suggests that binaural beats remain a promising, low-risk tool for probing auditory-driven neural dynamics and cognitive modulation. Further investigations are essential to map optimal protocols, mechanisms, and applications.

Data Availability and Supplementary Data

Study Characteristics: (a)

Author (Year)	Country	Population	Number of participants	Design	Outcome domain	Main findings
Beauchene et al. (2016)	USA	Healthy adults (19-46 years), normal vision/hearing	28	Experimental (EEG)	Visuospatial working memory, cortical connectivity	15 Hz binaural beats increased response accuracy and modified cortical networks.
Borges et al. (2023)	Brazil	Healthy adults (18-33 years), no disorders	30	Placebo-controlled crossover double-blind trial	Memory performance, EEG spectral density	No significant changes in memory task performance or EEG data.
Corona-González et al. (2021)	Mexico	Healthy students (19–24 years), no music experience	20	Experimental (EEG)	EEG power spectral density	No clear brainwave entrainment; connectivity changes detected.

Mallik & Russo (2022)	Canada	Participants with anxiety	163	RCT	Anxiety	Music with theta beats reduces anxiety more than music alone.
Melnichuk et al. (2025)	USA	Healthy participants	64	2x2x2x2 factorial, within-subjects crossover	Brain entrainment, sustained attention	Gamma beats improve attention; entrainment varies with parameters.
Perez et al. (2020)	Canada	Healthy adults (mean 27.4 years)	16	Single-blind active-controlled	Neural entrainment/connectivity, mood	Binaural beats elicit cross-frequency connectivity
Schwarz & Taylor (2005)	Canada	Healthy participants	18	Experimental	Auditory steady state responses	Binaural beats evoke steady-state responses.
Zhao & Van Hedger (2025)	USA	Healthy participants	N/A	Experimental	Attention, reading comprehension, and mood	Effects on attention, reading, and mood (details limited).

(b)

Author (Year)	**Country**	**Population**	**Number of participants**	**Design**	**Outcome domain**	**Main findings**
Dos Anjos et al. (2024)	France	Healthy adults (mean 32.42 years), normal hearing	28	Experimental (EEG), Within-subjects	EEG power/connectivity, relaxation	Intermittent pure tones yielded greater EEG power changes than binaural beats or white noise.
Hommel et al. (2016)	Netherlands	Students (18–27 years), normal	40	Experimental dual-task (binaural	Cognitive flexibility	High-frequency binaural beats

		sight/hearing		beat vs. control)		increase cognitive flexibility.
Kasprzak (2011)	Poland	Healthy males	20	Experimental (EEG)	EEG morphology (spectral density)	Binaural beats influence EEG morphology; follow-up effect observed.
Klichowski et al. (2023)	Poland	Healthy participants	920	Experimental	Cognitive performance	Reverse effect: home-use binaural beats impair cognitive performance.
Kraus & Porubanová (2015)	Slovakia	University students, healthy adults	40	Randomized controlled trial	Working memory capacity	Binaural beats improve working memory capacity.
López-Caballero & Escera (2017)	Spain	University students (20–31 years)	14	Experimental (EEG), Within-subject	EEG power, emotional arousal	No enhancement of EEG power or emotional arousal.
Padmanabhan et al. (2005)	UK	Surgical patients	108	RCT	Pre-operative anxiety	Binaural beat audio decreases pre-operative anxiety.
Venkatesan et al. (2025)	Netherlands	Non-clinical population	308	Single-blind randomized controlled	Anxiety, mood	Music with monaural beats has been shown to reduce anxiety and improve mood.
Vernon et al. (2014)	UK	Healthy participants (18-32 years)	22	Randomized controlled	EEG amplitude/peak frequency	No entrainment

(c)

Author (Year)	**Country**	**Population**	**Number of participants**	**Design**	**Outcome domain**	**Main findings**
Abd Hamid et al. (2025)	Malaysia	Young adults (18–35 years, undergraduate students)	29	Randomized controlled exploratory study using fMRI	Brain connectivity and cognitive enhancement	Alpha binaural beats modulated frontoparietal/visual-motor/multisensory connectivity for flexibility/attention; with white noise, modulated salience/default mode for focus/emotion
Badr et al. (2025)	UAE	Healthy undergraduates, right-handed, no disorders	45	Experimental (EEG)	Mental state classification, stress mitigation	Impact of binaural beats on stress mitigation using partial directed coherence and graph convolutional networks.
Chockboondee et al. (2024)	Thailand	Healthy adults (18–40 years), no illnesses	60	Randomized controlled trial	Cognitive function (ERPs: N200/P300)	Increased P300/N200 amplitudes, shortened latency/RT after 4 weeks
Jirakittayakorn & Wongsawat (2017)	Thailand	Healthy participants	N/A	Two experiments (EEG during listening, memory/emotion tasks)	Neural oscillations, working memory, and emotion	Induced gamma/beta in frontal/temporal; improved recall; emotion changes
Mahajan et al. (2021)	India	Healthy males	40	Randomized controlled	Executive functioning (Stroop accuracy/RT, P300/N400)	High-frequency binaural beats affect executive functioning.

Pratt et al. (2009)	Israel	Healthy participants (18-25 years)	18	Experimental	Cortical evoked potentials	Neural activity modulates the left temporal lobe.
Wang et al. (2022)	China	Healthy subjects	60	Between-subjects randomized	Working memory/vigilance, brain connectivity, fatigue	15 Hz binaural beats enhance connectivity in a state of fatigue.
Gao et al. (2014)	China	Healthy right-handed (19–26 years)	13	Experimental (EEG)	EEG activity; Conditional Mutual Information (CMI) Phase Locking Value (PLV) Relative Power (RP)	Connectivity changes; no clear entrainment in delta, theta, alpha, beta bands.

Table 1. *Study Characteristics of binaural beat studies among 3 continents: America (a), Europe (b), and Asia (c). This table summarizes the key characteristics of the 25. It includes details on authors, publication year, country of origin, population studied, sample size, study design, primary outcome domains, and main findings*.

Study Design and Protocols:

Author (Year)	**BB frequency**	**Carrier tone (Hz)**	**Duration**	**Sessions**	**Delivery**	**Control condition**
Abd Hamid et al. (2025)	9.55 Hz (alpha)	220.45	16 minutes	1	Noise-canceling headphones	None (comparison between ABB and AWN groups)
Badr et al. (2025)	16 Hz (beta)	250	7 min	1	Headphones	Control alertness without binaural beats
Beauchene et al. (2016)	5 Hz, 10 Hz, 15 Hz	240	5 minutes/condition (30 min total)	1	Stereo headphones	No sound, pure tone (240 Hz), classical music
Borges et al. (2023)	40 Hz (gamma)	400	10 min	1 (2 phases)	Stereo headset	Classical music without binaural beat
Chockboondee et al. (2024)	6 Hz (theta)	250	10 min	30 (daily over 1 month), 3 evaluations	Earphones	Silence (silent earphones)

Corona-González et al. (2021)	Theta (4.60 ±0.70 Hz), Beta (18.42 ±2.82 Hz)	500	20 min	2	Open-back headphones	Resting state
Dos Anjos et al. (2024)	50 Hz (gamma)	200	4 min	1	Noise-cancelling earphones	White noise
Gao et al. (2014)	1 Hz (delta), 5 Hz (theta), 10 Hz (alpha), 20 Hz (beta)	200	5 min	N/A	Stereo headphones	N/A
Hommel et al. (2016)	40 Hz (gamma)	340	3 min	1	In-ear headphones	Continuous tone (340 Hz)
Jirakittayakorn & Wongsawat (2017)	40 Hz (gamma)	250	30 min (Exp 1); 20 min (Exp 2)	1	Binaural audio	N/A
Kasprzak (2011)	10 Hz (alpha)	100	20 min	1	Stereo headphones	Silence
Klichowski et al. (2023)	15 Hz (beta, Study 1); 5 Hz (theta, Study 2)	240	~20-30 min (during tests)	1	Stereo headphones	Silence; classical music; pure tone
Kraus & Porubanová (2015)	9.55 Hz (alpha)	230	12 min	1	Stereo headphones	Sea sound without binaural beat
López-Caballero & Escera (2017)	4.53 Hz (theta), 8.97 Hz (alpha), 17.93 Hz (beta), 34.49 Hz (gamma), 57.3 Hz (upper-gamma)	373	3 min	1	Insert earphones	Acoustic beats, pink noise baseline
Mahajan et al. (2021)	25 Hz (beta)	250	20 min	1	Stereo headphones	No intervention (direct Stroop)
Mallik & Russo (2022)	Theta (4-8 Hz)	400	24 min	1	Online headphones	Pink noise
Melnichuk et al. (2025)	16 Hz (beta); 40 Hz (gamma)	340	33 min	2 (1 week apart)	Headphones	Pure tone

Padmanabhan et al. (2005)	0.1-4 Hz (delta)	400	30 min	1	Headphones	Soundtrack without binaural beat;no intervention
Perez et al. (2020)	7 Hz (theta); 40 Hz (gamma)	380	8 min	1 (5 blocks)	Insert earphones	Monaural beats
Pratt et al. (2009)	3 Hz and 6 Hz	250	2,000 ms	1	Earphones	N/A
Schwarz & Taylor (2005)	40 Hz	400	N/A	1	Earphones	Monaural beats
Venkatesan et al. (2025)	1.067 Hz (monaural)	219.465	30 minutes	1	Online headphones	Pure tone (220 Hz)
Vernon et al. (2014)	10 Hz (alpha); 20 Hz (beta)	400	1 min per segment (10 segments)	1	On-ear headphones	Single 400 Hz tone
Wang et al. (2022)	15 Hz (beta); 40 Hz (gamma)	240	20 min	1	Stereo headphones	Pure tone (240 Hz)
Zhao & Van Hedger (2025)	7 Hz (theta); 40 Hz (gamma); 0 Hz (control)	250	10 min	1	N/A	0 Hz control tone

Table 2. *This table summarizes the study designs and protocols of the 25 studies. It includes details on binaural beat frequency, carrier tone, duration, sessions, delivery method, and control condition.*

Abbreviations Table

Abbreviation	**Full Term**	**Definition**
EEG	Electroencephalography	Recording of brain electrical activity
fMRI	Functional Magnetic Resonance Imaging	Imaging technique measuring brain activity via BOLD signals

MEG	Magnetoencephalography	Recording of the magnetic activity of the brain
ERP	Event-Related Potential	EEG component time-locked to cognitive or sensory events
ASSR	Auditory Steady-State Response	Steady neural response generated by repetitive auditory stimuli
FFR	Frequency-Following Response	Brainstem-level response that follows frequency components of auditory stimuli
PLV	Phase-Locking Value	Measure of phase synchrony across trials
RCT	Randomized Controlled Trial	Experimental design with random participant allocation
RT	Reaction Time	Time required to respond to a stimulus
WM	Working Memory	Cognitive system for short-term manipulation of information
WMC	Working Memory Capacity	Capacity limit of working memory
DMN	Default Mode Network	Network active during rest and mind-wandering
BOLD	Blood Oxygen Level–Dependent	Signal measured in fMRI reflecting oxygenation changes
Hz	Hertz	Frequency unit
dB	Decibel	Unit of sound intensity
P300	P3 Component	ERP component related to attention and decision-making
N200 / N2	Negative 200 Component	ERP component associated with conflict and cognition

Acknowledgment

Not applicable

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Appendices

Search strategy

The search strategy was developed iteratively in consultation with a research librarian. It was tailored to each database using a combination of controlled vocabulary (e.g., MeSH terms in PubMed such as "Electroencephalography," "Cognition," and "Auditory Perception") and free-text keywords. Key search terms included variations of "binaural beats," "binaural beat stimulation," "auditory beats," "brain entrainment," "EEG," "brainwave modulation," "cortical connectivity," "cognitive enhancement," "memory performance," "attention," "anxiety," "stress mitigation," and "mood." Boolean operators were used to combine terms (e.g., "binaural beats"

AND (EEG OR "brain activity" OR cognition OR anxiety OR memory)). Filters were applied for human studies and publication dates from 2005 onward. An example PubMed search string was: ("binaural beats"[Title/Abstract] OR "auditory beat stimulation"[Title/Abstract]) AND (EEG[Title/Abstract] OR "brain entrainment"[Title/Abstract] OR cognition [Title/Abstract] OR anxiety [Title/Abstract] OR memory [Title/Abstract]) AND ("2005/01/01"[Date - Publication]: "2025/09/30"[Date - Publication]). The strategy was piloted and refined to ensure sensitivity and specificity, with reference lists of included studies hand-searched for additional relevant articles.