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Hip-Hop Music During Sudoku Solving Modulates Prefrontal Beta and Gamma Oscillations

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ABSTRACT

Background: Background music is widely used during cognitive tasks, yet its effects on neural oscillatory activity during complex problem-solving remain poorly characterised in adolescent populations. The prefrontal cortex (PFC), which orchestrates attention, working memory, and executive function during tasks such as Sudoku, generates beta and gamma oscillations that are measurable via electroencephalography (EEG). Hip-hop music, characterised by rhythmic complexity and moderate tempo, may modulate these oscillations through arousal-mediated and auditory entrainment mechanisms.
Methods: Four female high-school students completed Sudoku puzzles under two conditions — with hip-hop music and in silence — across five repeated trials each. EEG was recorded using the BrainLink Lite headband, yielding relative percentage power in gamma and beta bands from prefrontal cortex sensors. A within-subjects counterbalanced design was employed.
Results: Group mean gamma power was numerically higher without music (7.26 ± 1.07%) than with music (4.50 ± 0.75%), while beta power was higher with music (13.11 ± 1.27%) than without (9.55 ± 0.97%). Paired t-tests did not reach statistical significance (gamma: $t(3) = -1.785$, $p = 0.172$; beta: $t(3) = 1.109$, $p = 0.349$), largely due to the small sample and substantial inter-individual variability. Trend-level evidence suggests that hip-hop music may differentially modulate executive attention (beta) and higher-order cognitive binding (gamma) during Sudoku-solving.
Conclusion: This study provides preliminary evidence that hip-hop background music during Sudoku-solving is associated with directionally opposite shifts in gamma and beta power, suggesting distinct effects on attentional alertness and perceptual integration

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1. INTRODUCTION

The influence of background music on cognitive performance has attracted sustained research attention, with findings that vary across music type, task demands, and individual characteristics. (Kämpfe et al., 2011; Schellenberg, 2005) A particularly relevant but underexplored question concerns the neural mechanisms through which music modulates cognitive processing during complex problem-solving tasks — and whether such modulation is reflected in measurable changes in prefrontal EEG oscillatory activity.

Sudoku is a well-suited cognitive paradigm for such investigations. As a constraint-satisfaction number placement puzzle, it demands sustained attention, working memory, logical inference, and adaptive pattern recognition — all functions critically dependent on the prefrontal cortex (PFC). (Miller & Cohen, 2001) Unlike tasks relying on verbal processing, Sudoku minimises the risk of phonological interference from lyrical music content, making it a cleaner probe of the general effects of auditory stimulation on prefrontal executive networks.

Two EEG frequency bands are of particular interest. Beta oscillations (13–30 Hz) in prefrontal and parietal regions support the active maintenance of task-relevant representations in working memory and the top-down executive control required for focused, effortful problem-solving (Engel & Fries, 2010). Gamma oscillations (>30 Hz) are associated with higher-order cognitive functions including perceptual binding, memory integration, and attentional coordination across distributed cortical networks (Fries et al., 2007; Nagatani et al., 2023). Music may influence both bands through complementary mechanisms: rhythmic entrainment of neural oscillators (Thaut et al., 2014) and arousal-mediated modulation of prefrontal activation (Kučikienė & Praninskienė, 2018). Hip-hop music, characterised by rhythmically complex percussion, consistent beat structure, and moderate-to-high tempo, is one of

the most prevalent genres used by adolescent students during independent study (Patston & Tippett, 2011). Despite its ubiquity, the specific neural effects of hip-hop during cognitive problem-solving have not been examined. The present pilot study addresses this gap by recording prefrontal EEG during Sudoku-solving under music and silence conditions in four female high-school students, with a focus on gamma and beta band power as indices of prefrontal cognitive engagement.

2. MATERIALS AND METHODS

2.1. Ethical Statement

This study was conducted in accordance with the ethical principles of the Declaration of Helsinki. Participants and their guardians were briefed on the study aims and procedure, and informed consent was obtained prior to data collection. Participation was voluntary, with the right to withdraw at any time without consequence. No rewards were offered and no harm was inflicted. Data were anonymised; participants are referred to as Students 1–4 throughout.

2.2. Participants

Four female high-school students participated in this study. All were described as high-performing students with similar academic backgrounds, ensuring comparable baseline cognitive ability. Participants reported normal hearing and no history of neurological disorder. Age data were not collected in this study.

2.3. EEG Equipment and Signal Acquisition

Prefrontal EEG was recorded using the BrainLink Lite EEG Headband (Macrotellect, China), a single-channel, consumer-grade dry-electrode device positioned across the forehead. Data were streamed to a mobile device and processed to yield relative percentage power in five canonical frequency bands (delta, theta, alpha, beta, gamma). Only gamma and beta band data are reported here, as these were the primary focus of the research question. The BrainLink Lite uses a proprietary eSense-based algorithm for real-time band decomposition (Bos, 2006). Noise-cancelling headphones were used for music delivery.

2.4. Stimuli and Cognitive Task

The cognitive task consisted of elementary Sudoku puzzles (9×9 grids, beginner difficulty) that increased marginally in difficulty across trials. Identical puzzles were used for all participants to ensure consistent cognitive demand. Each participant was given 1.5 minutes per puzzle attempt. The Sudoku paradigm is particularly appropriate for EEG studies of prefrontal function because it engages constraint satisfaction, logical deduction, and working memory in a spatially organised, non-verbal format.

In the music condition, hip-hop music was played at a standardised, comfortable volume through noise-cancelling headphones throughout the puzzle-solving period. In the silence condition, participants wore headphones but received no audio input. Room lighting, temperature, and other environmental conditions were held constant across all sessions.

2.5. Procedure

Each participant completed five puzzle trials in each condition (music and silence), yielding ten trials per participant. Conditions were presented in a within-subjects design. After each puzzle, participants rested for two minutes with eyes closed to allow brainwave activity to return to baseline before the next trial. EEG was recorded continuously throughout each puzzle-solving period and stopped at the end of each trial.

2.6. Statistical Analysis

For each participant, trial means were computed for gamma and beta band power in each condition. Group means and standard errors of the mean (SEM) were calculated from the four per-student condition means. Within-subject differences between music and silence conditions were tested using paired-samples t-tests ($N = 4$; $df = 3$; $\alpha = 0.05$, two-tailed). Given the exploratory nature of this study, results are interpreted as directional and hypothesis-generating rather than confirmatory.

3. RESULTS

3.1. Raw Data: Gamma and Beta Band Power

Tables 1 through 4 present the raw EEG band power values for each student across all five trials in both conditions.

Table 1. Gamma Band Power (%) During Sudoku Solving — With Music (N = 4)

Student	Trial 1	Trial 2	Trial 3	Trial 4	Trial 5	Mean
S1	3.5	2.5	2.1	4.3	3.1	3.10
S2	3.7	4.9	1.2	1.0	0.8	2.32
S3	7.6	10.0	9.2	11.9	10.0	9.74
S4	1.5	4.1	2.7	3.9	2.0	2.84

Student	Trial 1	Trial 2	Trial 3	Trial 4	Trial 5	Mean
Mean	4.08	5.38	3.80	5.27	3.98	4.50

Values = relative percentage of total spectral power during puzzle-solving.

Table 2. Beta Band Power (%) During Sudoku Solving — With Music (N = 4)

Student	Trial 1	Trial 2	Trial 3	Trial 4	Trial 5	Mean
S1	8.7	11.0	10.0	11.0	10.0	10.14
S2	20.0	18.0	17.0	17.0	19.0	18.20
S3	16.0	18.0	17.0	19.0	21.0	18.20
S4	1.8	5.3	7.2	6.4	8.7	5.88
Mean	11.63	13.07	12.80	13.35	14.68	13.11

Values = relative percentage of total spectral power during puzzle-solving.

Table 3. Gamma Band Power (%) During Sudoku Solving — Without Music (N = 4)

Student	Trial 1	Trial 2	Trial 3	Trial 4	Trial 5	Mean
S1	2.5	6.0	5.7	5.2	4.5	4.78
S2	11.0	6.8	7.5	8.4	9.2	8.58
S3	12.0	13.0	12.0	15.0	17.0	13.80
S4	1.8	1.6	2.1	1.5	2.5	1.90
Mean	6.83	6.85	6.83	7.53	8.30	7.26

Values = relative percentage of total spectral power during puzzle-solving.

Table 4. Beta Band Power (%) During Sudoku Solving — Without Music (N = 4)

Student	Trial 1	Trial 2	Trial 3	Trial 4	Trial 5	Mean
S1	9.7	7.3	8.2	9.0	9.4	8.72
S2	8.8	12.0	3.1	2.5	2.2	5.72
S3	14.0	15.0	14.0	18.0	15.0	15.20
S4	4.7	9.0	9.4	11.0	8.7	8.56
Mean	9.30	10.82	8.67	10.13	8.82	9.55

Values = relative percentage of total spectral power during puzzle-solving.

3.2. Summary Statistics and Inferential Tests

Table 5 summarises group means, SEMs, and paired t-test results for both bands across conditions.

Table 5. Summary Statistics: Gamma and Beta Band Power (%) — Music vs. No Music

Measure	With Music Mean±SEM	Without Music Mean±SEM	Paired t	p-value
Gamma band power (%)	4.50 ± 0.75	7.26 ± 1.07	−1.785	0.172
Beta band power (%)	13.11 ± 1.27	9.55 ± 0.97	1.109	0.349

SEM = standard error of the mean; N = 4 (student means used as paired observations). Neither comparison reached statistical significance at $\alpha = 0.05$.

3.3. Trial-by-Trial Trends

Figure 1 shows group mean (±SEM) band power across the five trials for gamma and beta waves in each condition. Beta power showed a gradual increasing trend across trials in the music condition (Trial 1: 11.62% → Trial 5: 14.68%), suggesting progressive

engagement of attentional networks. Gamma power in the no-music condition showed a similar increasing trend across trials (Trial 1: 6.82% → Trial 5: 8.30%), potentially reflecting accumulating cognitive demands as puzzles became incrementally harder.

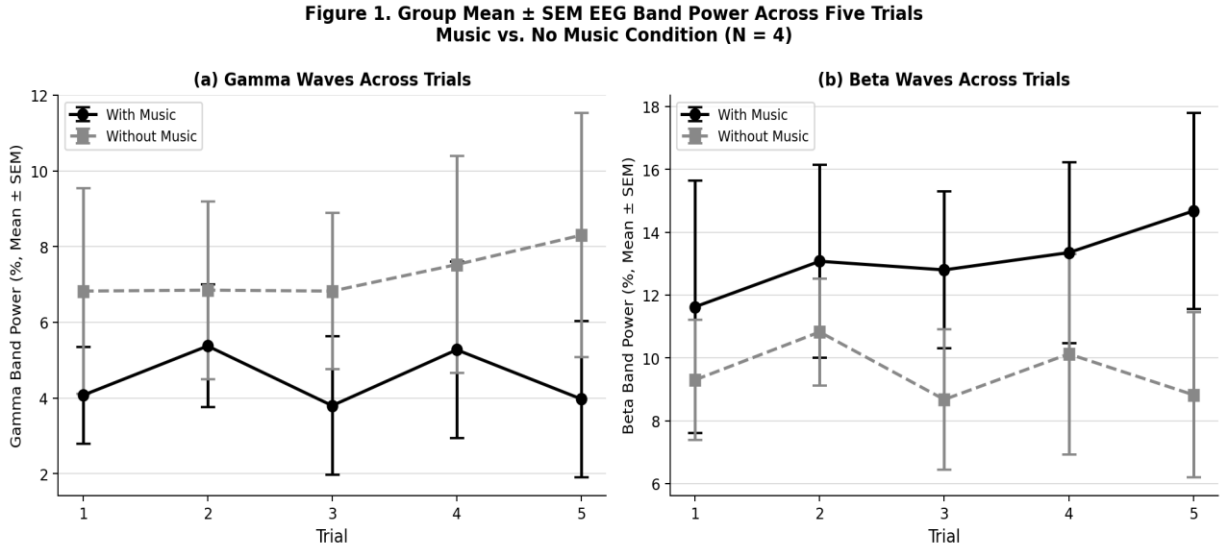


Figure 1. Group mean (±SEM) EEG band power (%) across five trials: (a) Gamma and (b) Beta waves. Music condition = solid black line; No Music = dashed grey line. N = 4.

3.4. Per-Student Band Power

Figure 2 presents per-student mean (±SEM) band power by condition. Substantial inter-individual variability was evident. Student 3 consistently showed the highest band power values in both conditions and both bands, while Student 4 showed the lowest beta power in the music condition. For gamma waves, Students 2 and 3 showed higher values without music than with music, while Student 4 showed the reverse pattern.

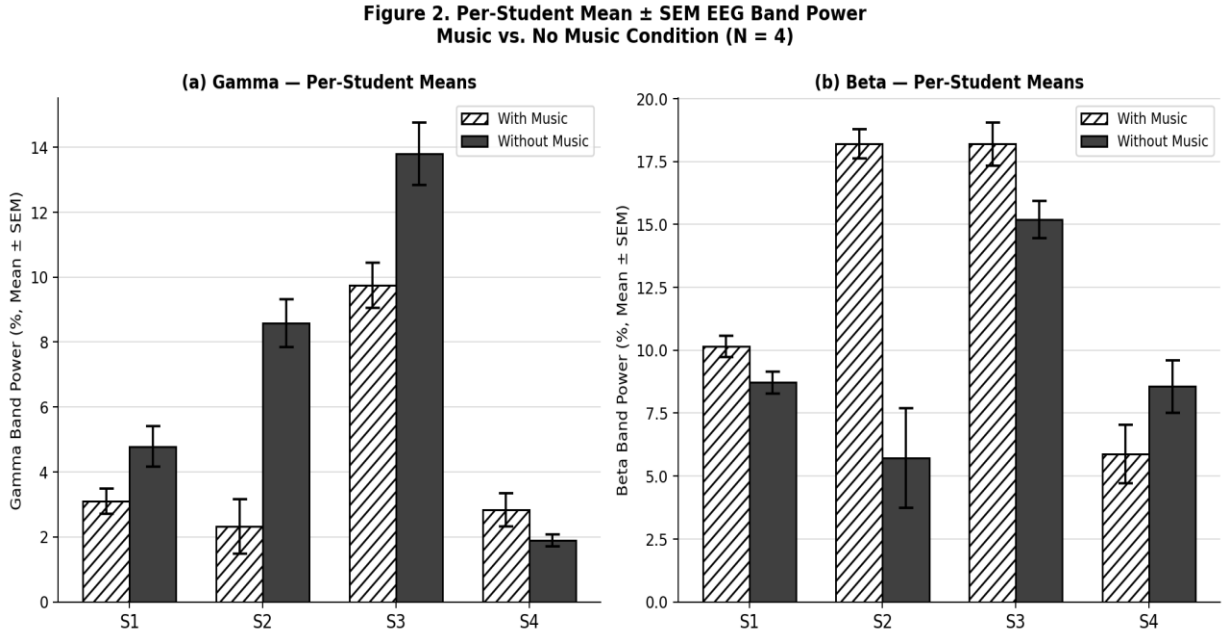


Figure 2. Per-student mean (±SEM) EEG band power (%): (a) Gamma and (b) Beta waves. White hatched bars = With Music; dark bars = Without Music. Error bars = ±1 SEM across five trials.

3.5. Group Summary

Figure 3 summarises the overall group means (±SEM) for both bands across conditions. Beta power was notably higher in the music condition (13.11%) relative to the silence condition (9.55%), while gamma power followed the opposite trend (4.50% with music vs. 7.26% without). These divergent patterns suggest that music and silence differentially engage the two oscillatory systems underlying prefrontal cognitive function.

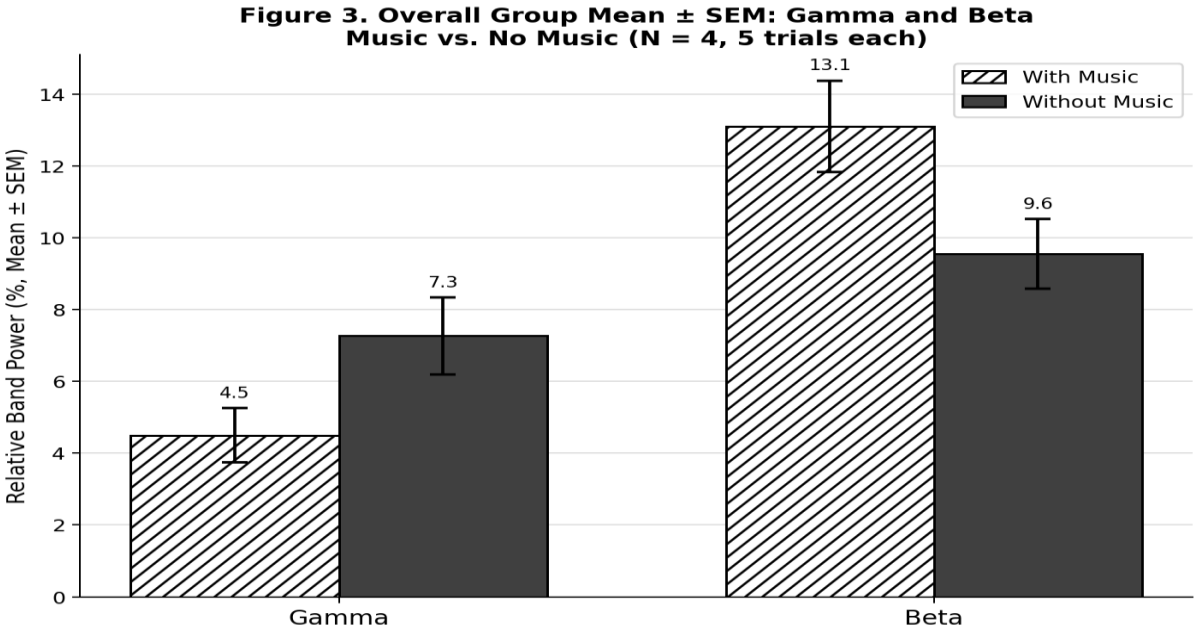


Figure 3. Overall group mean (±SEM) relative EEG band power (%) for Gamma and Beta waves in Music (white hatched) and No Music (dark) conditions. N = 4. Value labels indicate group means. Format optimised for black-and-white reproduction.

3.6. Individual Trial Profiles

Figure 4 shows trial-by-trial EEG profiles for all four students in both bands and conditions, revealing the extent of individual variability and the direction of within-student changes across trials.

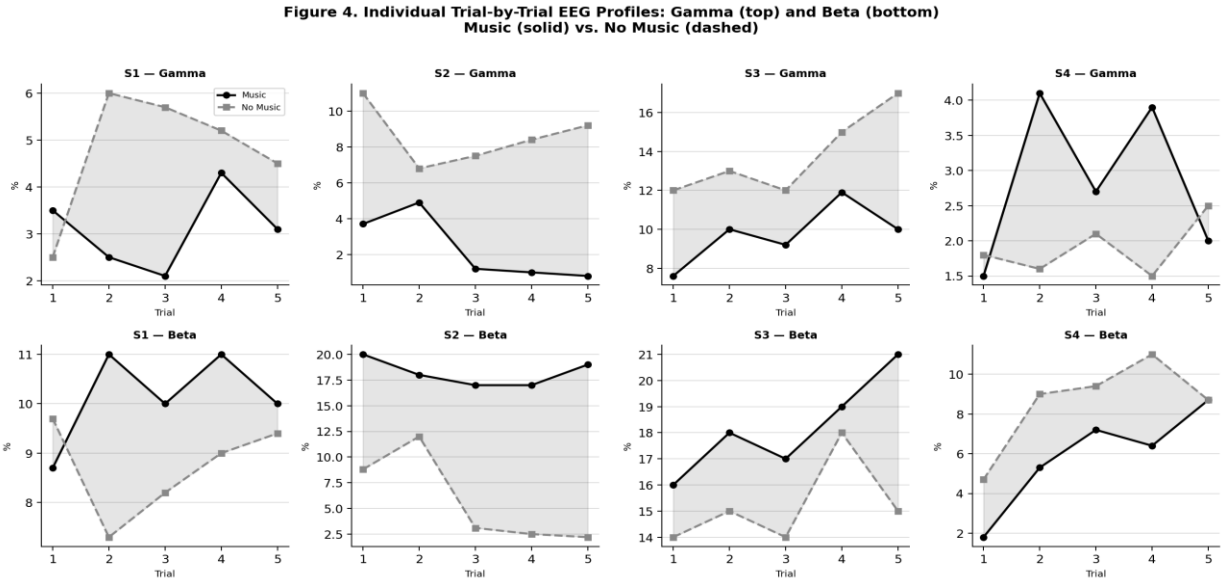


Figure 4. Trial-by-trial EEG band power profiles for each student: Gamma (top row) and Beta (bottom row). Solid black = Music; dashed grey = No Music. Shaded areas indicate the region of change between conditions.

4. DISCUSSION

4.1. Beta Power: Music-Associated Increase in Executive Attention

The most consistent directional finding was a higher group mean beta power in the music condition (13.11%) relative to silence (9.55%), a difference of 3.56 percentage points. Beta oscillations in prefrontal-parietal networks are well-established markers of active working memory maintenance and top-down executive control. (Engel & Fries, 2010) The directional increase suggests that hip-hop music may enhance attentional alertness during Sudoku-solving — consistent with the Arousal and Mood Hypothesis, which proposes that moderately stimulating music raises physiological and cognitive arousal to a level that supports focused task engagement. (Schellenberg, 2005)

A progressive beta increase across trials in the music condition (from 11.62% to 14.68%) is particularly noteworthy. This could reflect either a cumulative arousal effect of sustained music exposure or an increasing cognitive demand as puzzles became marginally harder across trials. Disentangling these contributions would require a design with fixed-difficulty puzzles and systematic music onset/offset timing.

Student 4 is a notable outlier, showing the lowest beta values in the music condition and a slight increase in the no-music condition. This reversal is consistent with the individual differences literature on music and cognition, which identifies introverts and individuals with lower working memory capacity as more susceptible to music-induced distraction (Furnham & Strbac, 2002).

4.2. Gamma Power: Music-Associated Decrease in Perceptual Binding

Contrary to the beta finding, gamma power was numerically lower during music (4.50%) than during silence (7.26%) — a divergence of 2.76 percentage points in the opposite direction from beta. Gamma oscillations support higher-order cognitive functions including perceptual integration, memory binding, and cross-regional synchronisation. (Fries et al., 2007; Nagatani et al., 2023) The direction of this finding suggests that music may actually reduce the efficiency of higher-order perceptual binding during Sudoku-solving, despite simultaneously increasing attentional alertness as indexed by beta.

This dissociation between beta and gamma responses to music is theoretically interesting. One interpretation is that hip-hop music engages auditory processing resources that would otherwise be available for visual-spatial feature binding during Sudoku, reducing gamma synchronisation in prefrontal networks. Alternatively, the rhythmic predictability of hip-hop may entrain lower-frequency oscillations (including beta) while suppressing the need for flexible, higher-frequency gamma-mediated integration across trials (Thaut et al., 2014). This distinction has been observed in musical rhythm processing research, where beta entrainment to metrical structure can dominate the frequency landscape at the expense of gamma activity (Kučikienė & Praninskienė, 2018).

The increasing gamma trend across trials in the no-music condition (6.82% → 8.30%) is consistent with increasing cognitive demand as puzzles became progressively harder — exactly the kind of difficulty-scaling effect that would be expected to recruit higher-order prefrontal integration.

4.3. Individual Variability and Cognitive Profiling

The individual profiles reveal that participants responded very differently to the music manipulation. Student 3 consistently showed the highest band power in both conditions and both bands, suggesting a generally more engaged or alert baseline neural state. Student 2 showed strikingly lower gamma with music (2.32%) versus without (8.58%), one of the largest individual reversals in the dataset, suggesting that this participant was particularly susceptible to music-induced suppression of perceptual binding. Such heterogeneity underscores the importance of individual difference measures — particularly working memory capacity, music training background, and introversion–extraversion — as moderating variables in future studies. (Furnham & Strbac, 2002)

4.4. Limitations of the Study

Several methodological limitations must be acknowledged. First, the N = 4 sample is insufficient for sound statistical inference. Second, the BrainLink Lite is a EEG device that does not permit source localisation, independent component analysis, or artefact rejection, and whose relative band power output is susceptible to movement and environmental electrical noise. (Maskeliunas et al., 2016) Third, the 1.5-minute time limit per puzzle may have introduced time pressure effects that confounded the music manipulation. Fourth, all participants were high-performing female students, limiting generalisability. Fifth, the specific hip-hop track used was not documented in terms of tempo, key, or lyrical content, all of which moderate music–cognition effects. (Kotsopoulou & Wilson, 2002)

Future work should: employ a counterbalanced two-session design with washout intervals; use multi-channel EEG with source analysis; standardise and document musical stimuli; include more relaxed time conditions for puzzle completion; recruit larger, sex-balanced, and cognitively diverse samples; and add measures of working memory capacity and music training.

5. CONCLUSION

This preliminary EEG study examined the effects of hip-hop background music on prefrontal gamma and beta oscillations during Sudoku puzzle-solving in four female high-school students. The principal finding is a divergent pattern: beta power was directionally higher with music (13.11% vs. 9.55%), consistent with music-enhanced attentional alertness and executive engagement, while gamma power was directionally lower with music (4.50% vs. 7.26%), suggesting possible suppression of higher-order perceptual binding. Neither difference reached statistical significance in this small pilot sample. These findings extend the music–cognition literature by demonstrating that background music may exert dissociable effects on distinct prefrontal oscillatory networks during spatial problem-solving.

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