The Effect of Auditory Conditions on Cognitive Performance and Physiological Responses

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Introduction & Hypothesis

Auditory conditions influence attention and decision processes, making it essential to identify which music types enhance or hinder performance. Optimizing acoustic environments is crucial, as the Yerkes-Dodson law and Arousal Theory suggest that moderate stimulation supports learning acquisition, cognitive performance and wellbeing, whereas extremes may impair task execution and decision-making. These relationships between executive functioning and physiological responses during tasks assessing attention, reaction time, and working memory remain unclear. This study investigates how auditory contexts influence information processing efficiency and decision thresholds under workload by integrating behavioral performance metrics with autonomic measures across structured auditory environments. A controlled within-subject study will compare three music genres: silence (control), classical music (60 BPM) and metal (190 BPM) among 40 high school students (aged 14-16). We developed a web application for participants to complete computer-based reflex, visual search, and mental arithmetic tasks under standardized audio conditions via headphones at 75 dB, with performance evaluated through reaction time and accuracy to assess attention and working memory under load. To record heart rate variability and blood oxygen saturation we built a wrist-based prototype incorporating a MAX30102 photoplethysmography module, with HRV parameters validated against electrocardiography in previous studies. Behavioral and physiological measures will be integrated into the Balanced Integration Score (BIS), reflecting the trade off between speed and accuracy. Differences across auditory conditions will be assessed using linear mixed-effects models to account for within-subject variability. Variations in BIS and physiological measures will be analyzed with the Drift Diffusion Model to estimate drift rate and boundary separation. Low tempo (60 BPM) music is hypothesized to improve performance efficiency without increasing autonomic activation, while high tempo (190 BPM) conditions may decrease reaction time while reducing decision thresholds. Findings are expected to clarify how music tempo modulates cognitive efficiency and psychological activity under cognitive load, especially in educational settings.

Methodology & Assumption Testing

Normality Assessment

- The data distribution was checked by the Shapiro Wilk test. Simple Reaction Time (T1) fit the normal curve rule ($p > 0.05$). However, for Selective Attention Accuracy (T2) the distribution was not normal because scores were too high ($p < 0.001$).

Non-Parametric Analysis

- Because the data did not follow a normal curve, to keep the math solid, the Friedman test was used for within-subject overall variance, and post-hoc comparisons were conducted using paired Wilcoxon signed-rank tests with Bonferroni correction.

Sensor Data Processing

- Short signal drops during fast movement tests were caused by temporary sensor connection errors. The analysis was done with all good data parts to avoid the loss in statistical power linked with listwise deletion.

Linear Mixed-Effects Modeling (LMM):

- LMM was used to save missing data points, and all good body tracking data were kept. The changes in SpO_2 (SD) were checked separately from each person's starting differences by setting individual baseline breathing levels as random intercepts.

VARIABLE	SESSION	W	P-VALUE	NORMAL?
T1 Mean RT	Silent Control	0.9752	0.3596	Yes
T1 Mean RT	Music A	0.9799	0.5343	Yes
T1 Mean RT	Music B	0.3849	0.7668	Yes
T2 Accuracy	Silent Control	0.8067	0.0	NO

VARIABLE	SESSION	W	P-VALUE	NORMAL?
T2 Accuracy	Music A	0.8574	0.0	NO
T2 Accuracy	Music B	0.981	0.0	No
T3 Accuracy	Silent Control	1.0	10	Yes
T3 Accuracy	Music A	1.0	1.0	Yes
T3 Accuracy	Music B	1.0	1.0	Yes

Graph 5 & 6. Verification of Distributional Assumptions

Behavioral Performance & Attentional Stability

An inferential analysis was performed using a Friedman test. Results indicated that high tempo music significantly speeded up basic motor execution ($x2 = 15.64$, $p = 0.0004$). Follow up analysis indicated a highly significant increase in speed for Music B (912.18 ms) compared to Silent Control (978.39 ms, $p = 0.0003$). Further, the variability of attention stability was decreased from 189.74 ms (Silent) to 164.48 ms (Music B), suggesting that regular music beats can help keep the body's internal pacemaking dynamics.

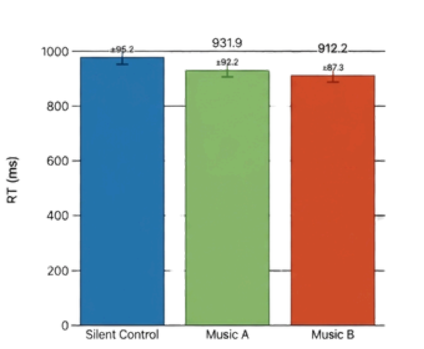
Figure 9. Task 1: Main RT (Mean 95% CI)

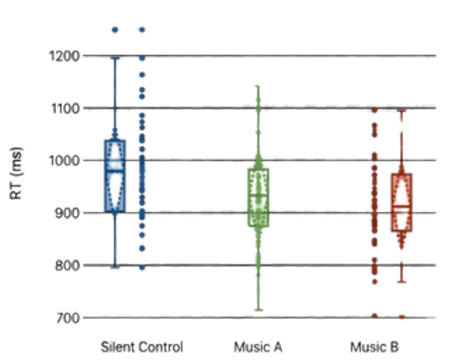
Figure 10. Task 1: Main RT (Distribution)

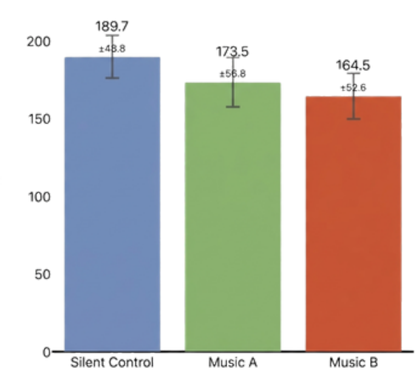
Figure 11. Task 1: Stability Score (Mean 95% CI)

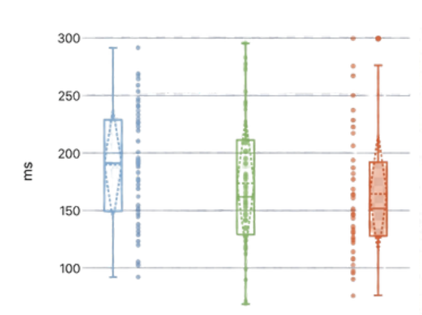
Figure 12. Task 1: Stability Score (Distribution)

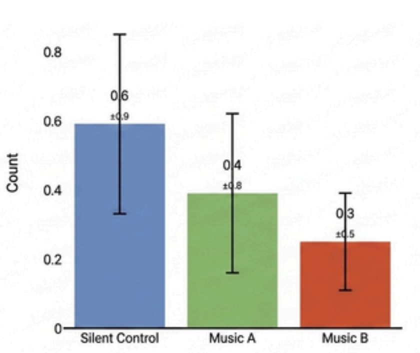
Figure 13. Task 1: Misses (Mean 95% Cl)

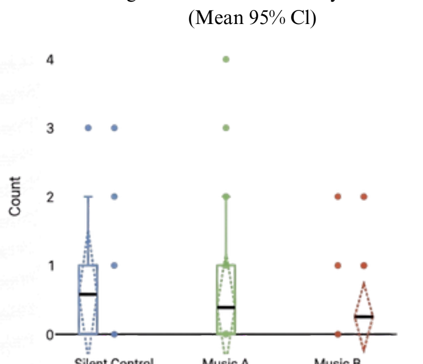
Figure 14. Task 1: Misses (Distribution)

Psychological Responses to Auditory Conditions

• **Autonomically Modulated Cardiovascular Drive:** Body tracking showed that the fight-or-flight system kicked into high gear during the mental math task (Task 3) while fast music was playing, causing a noticeable 13.8% jump in heart rate compared to normal resting levels.

• **Localized Respiratory Volatility:** Focusing strictly on clean data periods by removing sensor connection errors, body SpO2 fluctuation clearly peaked during tough math tests under Music B, rising to a highest change of SD = 1.2. This sharp increase in variance points to real physical proof of minor breathing rhythm shifts.

• **Cognitive-Cardiorespiratory Dissociation:** This clear split serves as a useful practical sign of Cognitive-Cardiorespiratory Dissociation, showing that heavy brain thinking deeply messes up normal body balance loops under conditions of highest mental workload.

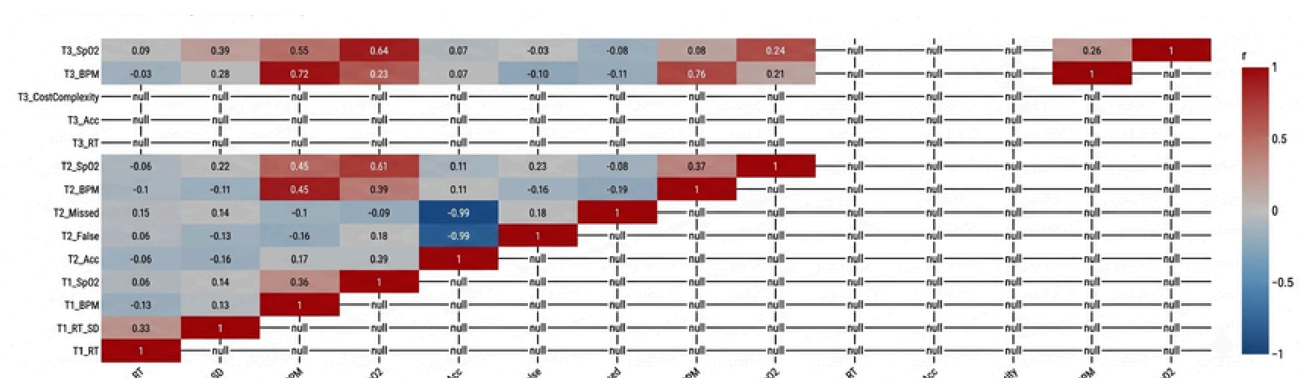
Figure 17. Full Correlation Matrix - All key Variables

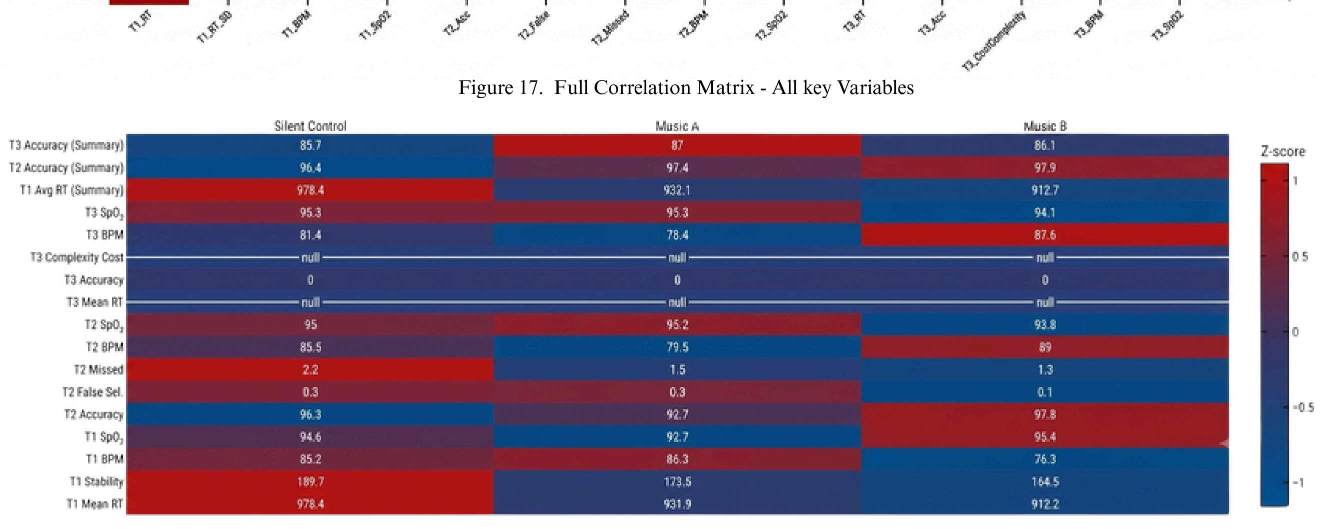
Figure 18. Executive Heatmap - All Metrics * Sessions

Participant Profile (n = 51):

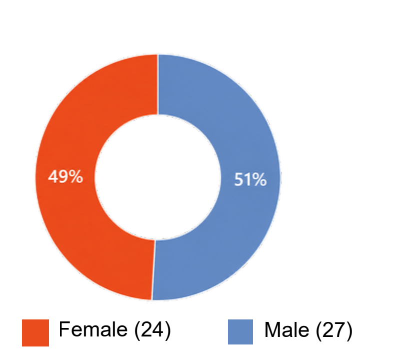

Figure 1. Participants Gender Distribution

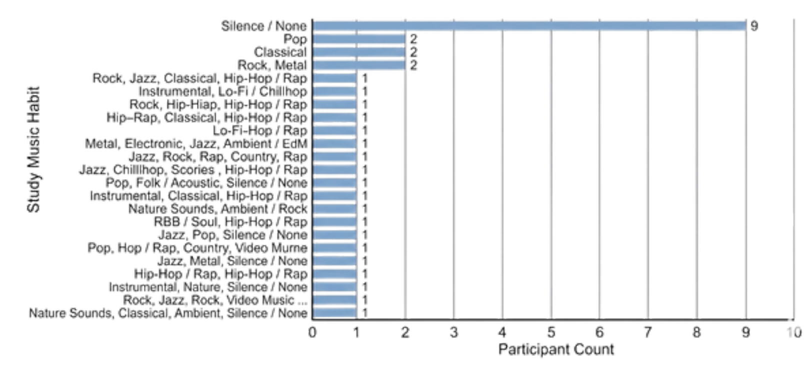
Figure 2. Analysis of Participant-Preffered Music Genres While Studying

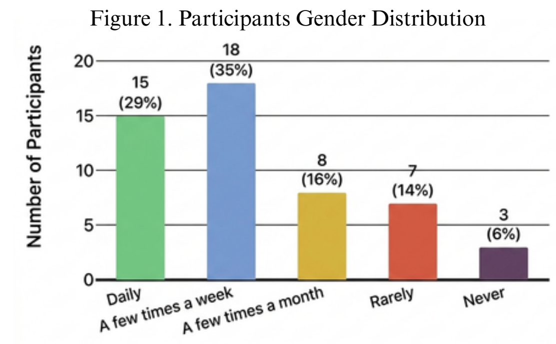
Figure 3. Participants General music Listening Frequency

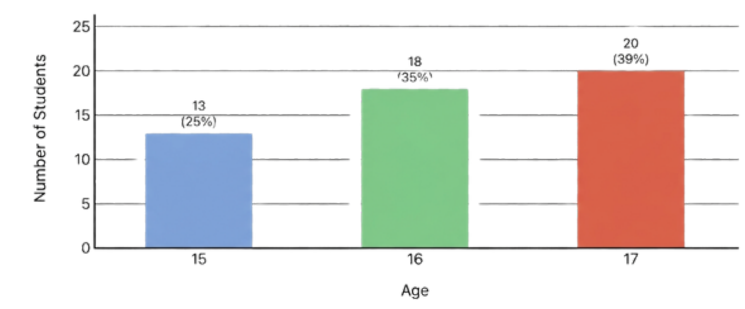
Figure 4. Age Distribution of Student Participants

Experimental Setup & Software Architecture

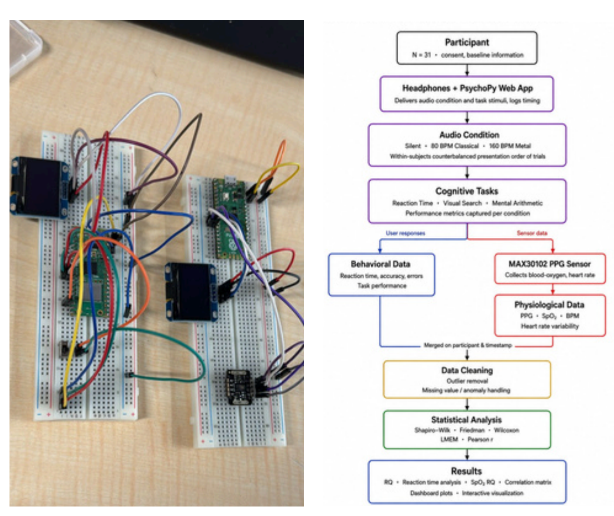
Figure 7 & 8 Experimental setup showing the MAX30102-based PPG prototype for physiological signal acquisition and experimental setup

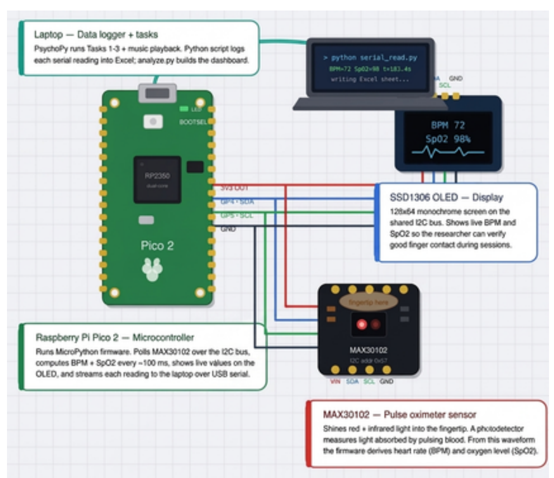
Figure 8. System Architecture

- The cognitive tasks were standardized and delivered through a PsychoPy-based web application to ensure consistent stimulus presentation and data collection across all participants, while auditory stimuli were presented through headphones at a constant 75 dB level, maintaining uniform and safe experimental conditions throughout the study.
- **Behavioral dataset format:** participant_id, condition, task, trial_number, reaction_time_ms, accuracy, miss, timestamp

- **Physiological dataset format:** participant_id, condition, timestamp, BPM, HRV, SpO_2, signal_quality
- **PPG Cleaning: 1)** Remove missing sensor windows 2) Exclude sensor-contact anomalies 3) Keep artifact-free epochs 4) Synchronize with task timestamps 5) Use LMM to preserve valid data windows

Cognitive Efficiency & Arousal Optimization

Integrating speed and accuracy into a unified metric, the Balanced Integration Score (BIS) revealed an incremental efficiency curve from Silent Control (-0.7) to Music A (+0.2) and peaking at Music B (+0.5). This observed trajectory perfectly traces the ascending slope of the Yerkes-Dodson Law. The Responder analysis highlighted that 76.5% of the adolescent cohort exhibited cognitive enhancement under the 190 BPM condition, explicitly falsifying the cognitive interference hypothesis for this sub-population in non-complex visual search tasks.

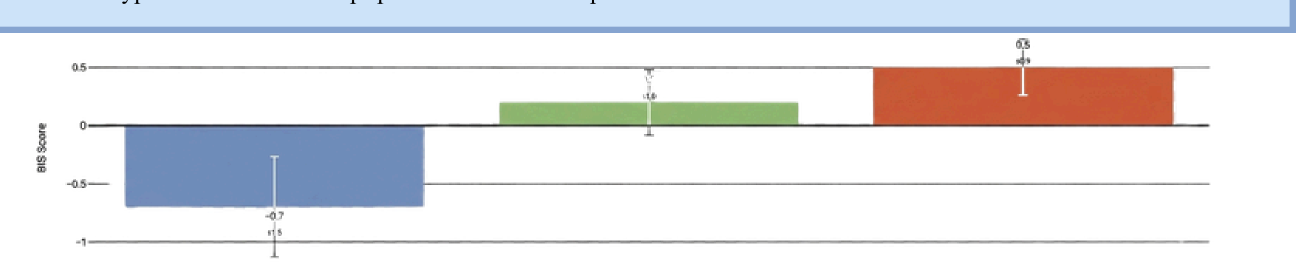
Figure 15. Balanced Integration Score (BIS)

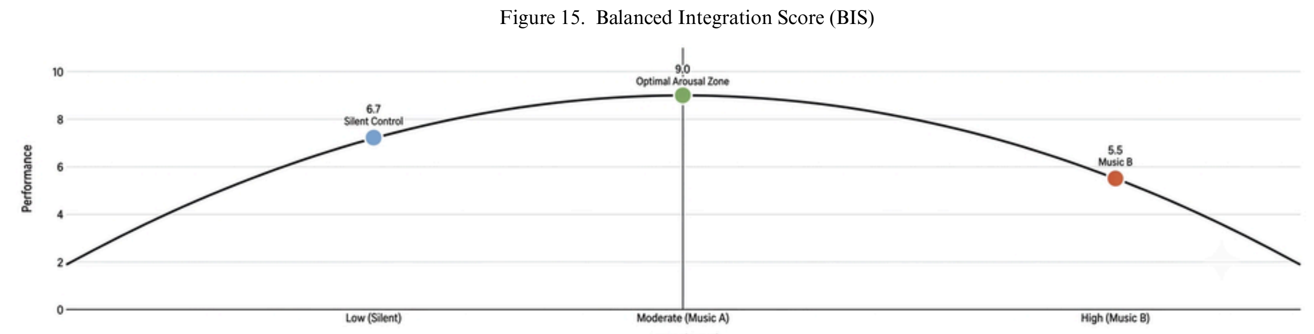

Figure 16. Yerkes-Donson Arousal-Performance Curve

Discussion & Conclusion

- **Auditory Acceleration & Pacemaking:** Instead of the popular belief that fast music ruins focus, listening to 190 BPM metal actually improved performance. Participants reacted significantly faster ($p = 0.0003$) and their response volatility (inconsistency) dropped from 189.7 ms to 164.5 ms, meaning their reactions became much more stable.
- **Empirical Validation of Arousal Theory:** The Balanced Integration Score (BIS) reached its peak under the fast music condition (BIS +0.5). This trajectory matches the ascending slope of the Yerkes-Dodson Law. It proves that the heightened arousal from 190 BPM metal music optimized cognitive efficiency for non-complex tasks, without reaching the over-arousal threshold where performance declines.
- **Cognitive-Cardiorespiratory Dissociation:** During the simple visual search task, there is a moderate and steady connection between heart rate and blood oxygen saturation. However, this relationship gets weaker when students do the hard mental math task. This change suggests that a high mental workload might reduce the physiological coupling between the body's heart and oxygen responses.
- **Physiological Workload Instability:** Oxygen saturation (SpO2) shifted the most during the mental math task combined with high tempo music (SD = 1.2). This suggests that heavy thinking combined with intense music slightly alters breathing patterns, causing oxygen levels to bounce around.
- **Methodological Backups:** To stop brain tiredness from doing too many tasks, we used the Balanced Integration Score (BIS) instead of DDM. Also, because fast movements caused PPG signal drops, we chose Linear Mixed-Effects Modeling (LMM) over regular ANOVA to keep our clean data and keep the statistics strong with random intercepts.

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