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TuningIn: Investigating the Effects of Auditory Stimuli on Adolescent Cognition

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ABSTRACT

The primary goal of the preliminary TuningIn study was to examine the physiological and cognitive effects of various sound cues on adolescents. A sample of 35 adolescents completed a survey that included several online tests. Each of these tasks measured cognitive flexibility/inhibition, analytical ability, and short-term memory, and subjects took the tests after listening to short amounts of silence, nature sounds, and their favorite songs. At the beginning and end of each session, participants' heart rate and blood pressure were recorded before and after listening to auditory stimuli to measure the physiological effects. When listening to calm nature sounds, subjects tended to exhibit higher levels of cognitive flexibility and mathematical understanding ($p < 0.001$). However, memory results did not improve to a comparable extent. Further, performance improved after subjects were asked about their favorite songs. It was also found that the energy level of song choices played a significant role in performance, indicating that personal preference affects the benefits of auditory stimuli. Beyond cognition, there was a clear decrease in heart rate upon listening to music of one's choice ($p = 0.009$), indicating that preferred music can induce relaxation. These findings suggest that listening to calming preferred music and nature sounds may both enhance adolescent cognition and reduce the intensity of physiological stress responses.

INTRODUCTION

Purpose

Music is a staple of global culture that can offer comfort and relaxation, potentially reducing anxiety. About 61% of U.S. high school students report feeling stressed about attaining good grades, while 59% report feeling stressed about attending four-year universities (Horowitz & Graf, 2019). National survey data indicate that 31.9% of adolescents aged 13-18 experience anxiety disorders (Merikangas, 2010). This underscores the necessity to identify accessible methods to reduce stress and preserve cognition. Auditory stimuli may be one such method. To test this hypothesis, this preliminary study investigated how audio stimuli, ranging from preferred music to naturalistic sounds, affected overall adolescent performance on various cognitive tests.

Auditory Processing

Auditory cues indirectly activate several brain regions. After entering the cochlea, auditory stimuli are detected by the brainstem as a combination of numerous elements, such as pitch and timbre. The newly encoded auditory information then travels to the primary auditory cortex (A1), which can engage the mesolimbic system. Within this pathway, the nucleus accumbens (NAc) codes for reward value and motivational salience. In doing so, the NAc also interacts with a broad cortical network including the prefrontal cortex (PFC), amygdala, and hippocampus (Warren, 2008). The hippocampus helps the brain store memories of auditory stimuli, and the ventral tegmental area (VTA) sends dopaminergic projections to the NAc and the amygdala. Dopamine is a neurotransmitter associated with stronger attention, spatial awareness, and working memory (Salimpoor et al., 2011; Ott & Nieder, 2019).

Auditory stimuli may activate other networks, however. Pleasant music can stimulate the release of endorphins and cortisol, promoting relaxation (Davis & Thaut, 1989). Furthermore, listening to peaceful naturalistic environments, such as rainforests, can provide benefits as illustrated by Attention Restoration Theory (ART). ART suggests that exposure to nature can replenish attentional resources through its lack of lyrics and unoccupied environment, which can mitigate cognitive fatigue (Liu et al., 2024). This illustrates auditory stimuli's influence on higher-order cognitive processes. Thus, modulating these systems may influence performance on cognitive tasks by catalyzing interactions among these auditory, limbic, and prefrontal neural networks.

Auditory Cognition

Studies suggest that noise exposure can have neutral to negative effects on cognitive performance in adults (Takahashi et al., 2001; Jennings et al., 1988), but findings have been inconsistent. Other studies have shown the effects of temporal auditory processing, which involves gauging the timing, duration, or sequence of sounds, on cognitive processing. While it is currently unknown how these two systems interact, auditory processing has been shown to improve language and memory (Davidson & Souza, 2023), likely because registering and responding to speech demands attention. The auditory cortex discriminates relevant noise in its environment, and its communication with neural networks indirectly stimulates memory and attention (Davidson & Souza, 2023). As a result, auditory processing may be positively associated with cognitive function. Because music demands high levels of auditory processing, scientists have paid closer attention to the biological benefits of auditory stimuli.

Clinical Research on Music

Music therapy is a viable means to ameliorate psychological struggle. It has been widely used in the medical field, generally in conjunction with antidepressants and psychotherapy. Music therapy has been attributed to short-term benefits against nervous system disorders, such as depression (Aalbers et al., 2017) and Alzheimer's disease (Moreira, 2018) as a mnemonic aid.

While listening to music can act as an anxiolytic through stress hormone release, it can also increase arousal levels, boosting physiological alertness. The arousal-mood hypothesis states that cognitive improvement depends on arousal and mood changes (Chee, 2024), suggesting that listening to

emotionally moving music can influence one's thinking ability. Preferred music can also stimulate the autonomic nervous system's default mode network (DMN) state (Chee, 2024), which is connected to increases in creativity and inventiveness (Zaatar et al., 2023; Immordino-Yang et al., 2012).

Music Training

Furthermore, higher musical awareness has shown promise as a catalyst for executive functions. Music training is associated with plastic change in the auditory and motor cortices, and these benefits likely stem from the unique education of rhythm, melody, and tempo (Miendlarzewska & Trost, 2014). Individuals who played instruments or studied music theory from a young age are more adept at cognitive tasks that gauge creativity and awareness (Kraus & Chandrakesan, 2010). Thus, greater musical experience likely enhances cognitive capacity. In contrast, comparatively few studies have examined adolescents' responses to music. One study found that music training significantly enhanced adolescents' intelligence (Müllensiefen, 2022), but it did not account for the adolescent population without training. Moreover, another study measured adolescents' emotional responses to different types of music (Wei et al., 2025). The findings reflected an inconclusive relationship between audio type and emotional responses, and the study did not explore music's effects on cognition.

The main hypothesis for this preliminary study was that nature sounds would yield the greatest improvements in cognitive performance by optimizing arousal while simultaneously reducing stress. It was also predicted that stress responses and performance would be negatively correlated; that is, if heart rate or blood pressure dropped, cognition would improve. Lastly, it was hypothesized that the energy of one's favorite song would change subjects' performance in a way aligned with the Mozart Effect (Nantais & Schellenberg, 1999), which suggests that one specific genre and/or energy level can potentially optimize cognition. Regardless of music training, simply listening to auditory stimuli before engaging in cognitive tasks may be sufficient for this age group to relax and focus. This study primarily aimed to illustrate a means for students to optimize their pre-test cognition through auditory stimuli.

METHODOLOGY

Classification

The study employed a quantitative, positivist framework with a within-subject repeated-measures design. Cognition was assessed using objective measures, including task completion time, accuracy, and physiological metrics. Participants provided informed consent, and results were disclosed only with their permission. Further, participants' personal information was removed from datasets to maintain confidentiality. The only physiological data taken were heart rate (bpm) and blood pressure (mmHg), and all participants had no preexisting blood conditions that prevented these measurements.

Study Population/Logistics

The study population consisted of adolescents in northern New Jersey aged 14-19. Participants with hearing impairments and complete colorblindness were not eligible since the Stroop test requires color

recognition. A sample of 35 students (n = 35) took the tests in a cross-sectional, repeated-measures design. Sessions were completed during school hours and in the evening. Each participant completed the tests in a single session, lasting approximately 25 minutes to prevent mental exhaustion. Sessions were held in quiet, isolated areas, so the subjects' primary stimuli were the assigned audio cues.

The three tests were administered in triplicate, where participants listened to silence, nature sounds, or preferred music. Nature sounds included waterfalls and rainforest birdsong. Each subject was asked for their favorite song, which would serve as preferred music. Subjects listened to stimuli for 50 seconds before each test. Sound levels were also regulated to stay below the Threshold Limit Value (TLV) for occupational noise exposure (85 dBA). To eliminate the confounding variable of simply gaining experience with each test, the order of audio cues participants listened to was randomized using a computer-generated sequence. Thus, some participants listened to nature sounds second, while others did so third. The sequences in which participants took the tests were not recorded. However, the sequence of cognitive tasks was held constant to maintain equal time intervals between trials. This way, subjects would not have an unfair advantage by attempting tests earlier or later.

Cognitive & Physiological Monitoring

Prior to measurement of subjects' blood pressure and heart rate, they were seated and given a summary of the study. This ensured understanding of the instructions and provided resting heart rates not influenced by recent physical activity, such as running. Two dependent variables were the time taken to complete a Stroop test and a mental mathematics quiz. The Stroop task assessed cognitive inhibition by having participants read the font colors of a panel of words, where the words spelled out colors different from the font (Scarpina, 2017). The mathematical assessment consisted of grade-appropriate problems in arithmetic, geometry, algebra, and applied reasoning. Subjects were also evaluated based on their score on the Human Benchmark - Sequence Memory Test, which uses a 3 x 3 grid of boxes that blink in a pattern. Usually, musical notes play alongside every blink, but they were silenced to eliminate external auditory stimuli. Participants attempted to follow this pattern, with sequences lengthening with each step. Because the task order was randomized, heart rate and blood pressure were only measured after the entire session to evaluate the physiological effects of generally pleasurable auditory exposure, eliminating the variable of prior audio cues changing individual trial results.

Equipment

General computers administered the tests through Google Forms, and a CVS Health digital monitor cuff measured each subject's blood pressure and heart rate to assess the effects of auditory stimuli on their physiology. While listening to audio cues, participants wore BOSE QC Headphones, which were removed during each cognitive task.

Statistical Analysis

Significant differences between performance following each cue were determined through one-way repeated-measures analysis of variance (ANOVA) and post hoc pairwise t-tests, with statistical significance defined as $p < 0.05$ and practical effect sizes measured as $\omega^2 > 0.01$. The ANOVA test was

administered first to gauge a significant difference across auditory conditions, and pairwise t-tests were used afterward to measure differences between specific pairs among the groups. For ANOVA, wider standard deviations of performance data were addressed by the Greenhouse-Geisser correction. For pairwise t-testing, the Holm correction was utilized to reduce the risk of false positives. Pearson correlation analyses were performed to determine associations between energy levels, heart rate changes, and performance changes. All analyses were conducted using XLMiner Analysis ToolPak and JASP.

For each song selected by the participant, a wide spectrum of musical tastes was accounted for by measuring songs' energy levels. These were obtained by examining the Spotify Web API in Python for each song's "energy percentage" (0.0 to 1.0). Then, these energy levels were compared with performance to examine whether energy levels also affected cognition.

RESULTS

Figure 1: Averages

	Stroop (s)	Math (s)	Memory (score)
Silence	6.553	76.522	11.714
Nature	5.361	65.885	10.743
Preferred	5.653	66.222	11.486

1A: This table shows the mean performances, in seconds or points, of the 35 participants. In the Stroop and mathematical tasks, participants performed better after listening to audio cues, with nature sound performance slightly outperforming that of favorite songs. However, on average, participants performed best on the memory test without audio cues. However, given that this test is scored by whole-number points, variation between testing groups was much smaller than that of the other two tests.

	Heart Rate (bpm)	Systolic Blood Pressure (mmHg)	Diastolic Blood Pressure (mmHg)
Before	77.686	120.486	69.429
After	72.857	118.657	70.6

1B: This table shows the physiological averages of subjects' heart rate (bpm), systolic blood pressure (mmHg), and diastolic blood pressure (mmHg), before and after the tests. The heart rate average decreased after subjects completed the tests under the influence of auditory stimuli. The systolic blood pressure slightly decreased, while the diastolic blood pressure slightly increased.

Figure 2: ANOVA Tests

Stroop ANOVA

Within Subjects Effects

Cases	Sphericity Correction	Sum of Squares	df	Mean Square	F	p	ω²
Audio	None	27.05	2.000	13.52	22.01	< .001	0.1069
	Greenhouse-Geisser	27.05	1.907	14.18	22.01	< .001	0.1069
Residuals	None	41.78	68.00	0.6144			
	Greenhouse-Geisser	41.78	64.83	0.6444			

Note. Type III Sum of Squares

Between Subjects Effects

Cases	Sum of Squares	df	Mean Square	F	p
Residuals	167.8	34	4.935		

Note. Type III Sum of Squares

Descriptives

Descriptives

Audio	N	Mean	SD	SE	Coefficient of variation
Silence	35	6.554	1.469	0.2484	0.2242
Nature Sounds	35	5.361	1.318	0.2228	0.2459
Favorite Song	35	5.653	1.506	0.2545	0.2663

Assumption Checks

Test of Sphericity

	Mauchly's W	Approx. X^2	df	p-value	Greenhouse-Geisser ε	Huynh-Feldt ε	Lower Bound ε
Audio	0.9511	1.654	2	.437	0.9534	1.000	0.5000

Math ANOVA

Within Subjects Effects

Cases	Sphericity Correction	Sum of Squares	df	Mean Square	F	p	ω²
Audio	None	2559▪	2.000▪	1280▪	3.391▪	.039▪	0.01001
	Greenhouse-Geisser	2559	1.632	1568	3.391	.050	0.01001
Residuals	None	$2.566\times10^{+4}$	68.00	377.3			
	Greenhouse-Geisser	$2.566\times10^{+4}$	55.50	462.3			

Note. Type III Sum of Squares

▪ Mauchly's test of sphericity indicates that the assumption of sphericity is violated (p < .05).

Between Subjects Effects

Cases	Sum of Squares	df	Mean Square	F	p
Residuals	$1.477\times10^{+5}$	34	4343		

Note. Type III Sum of Squares

Descriptives

Descriptives

Audio	N	Mean	SD	SE	Coefficient of variation
Silence	35	76.52	49.16	8.310	0.6425
Nature Sounds	35	65.89	37.30	6.304	0.5661
Favorite Song	35	66.22	35.92	6.071	0.5423

Assumption Checks

Test of Sphericity

	Mauchly's W	Approx. X²	df	p-value	Greenhouse-Geisser ε	Huynh-Feldt ε	Lower Bound ε
Audio	0.7748	8.421	2	.015	0.8162	0.8517	0.5000

Memory ANOVA

Within Subjects Effects

Cases	Sphericity Correction	Sum of Squares	df	Mean Square	F	p	ω²
Audio	None	18.06	2.000	9.029	0.4847	.618	0.000
	Greenhouse-Geisser	18.06	1.830	9.867	0.4847	.601	0.000
Residuals	None	1267	68.00	18.63			
	Greenhouse-Geisser	1267	62.22	20.36			

Note. Type III Sum of Squares

Between Subjects Effects

Cases	Sum of Squares	df	Mean Square	F	p
Residuals	1826	34	53.70		

Note. Type III Sum of Squares

Descriptives

Descriptives

Audio	N	Mean	SD	SE	Coefficient of variation
Silence	35	11.71	5.199	0.8789	0.4439
Nature Sounds	35	10.74	4.792	0.8100	0.4460
Favorite Song	35	11.49	6.400	1.082	0.5572

Assumption Checks

Test of Sphericity

	Mauchly's W	Approx. X^2	df	p-value	Greenhouse-Geisser ε	Huynh-Feldt ε	Lower Bound ε
Audio	0.9072	3.215	2	.200	0.9151	0.9645	0.5000

2A-C: This figure displays the results of repeated-measures ANOVA testing across all administered cognitive tests. P-values indicate statistical significance, and ω^2 indicates effect sizes. Auditory stimuli demonstrated a significant effect on Stroop performance and a strong effect size ($p < 0.001$, $\omega^2 = 0.107$, $F(2, 68) = 22.005$). Mauchly's test revealed that sphericity was violated in the mathematical task ($p = 0.015$), so the Greenhouse-Geisser correction was applied. Still, auditory stimuli demonstrated a mildly

significant effect on performance with a small effect size ($p = 0.05$, $\omega^2 = 0.010$, $F(2, 68) = 3.393$). Conversely, auditory stimuli yielded no significant effect on memory performance ($p = 0.618$, $\omega^2 = 0.000$, $F(2, 68) = 0.485$).

Figure 3: Post Hoc Pairwise Comparisons

Comparison Group	Stroop Task p-value	Math Task p-value
Silence vs Nature	$p < 0.001$	$p = 0.015$
Silence vs Favorite Music	$p < 0.001$	$p = 0.038$
Nature vs Favorite Music	$p = 0.110$	$p = 0.825$

3A: This table shows pairwise t-tests for performance on the first two tests (which ANOVA found to be significant) under each auditory influence. Statistically significant tests included the Stroop task between silence and nature ($p < 0.001$) and between silence and preferred music ($p < 0.001$). The mathematics task also showed significant differences between silence and nature ($p = 0.015$) and between silence and preferred music ($p = 0.038$). The Stroop task showed no significant difference between nature and preferred music, and there was also no significant difference between the nature and preferred music results across all three tests.

Post Hoc Tests

Stroop

Post Hoc Comparisons - Audio

			95% CI for Mean Difference					
		Mean Difference	Lower	Upper	SE	df	t	P_{Holm}
Silence	Nature Sounds	1.193	0.6713	1.714	0.2070	34	5.761	< .001
	Favorite Song	0.9003	0.4582	1.342	0.1756	34	5.128	< .001
Nature Sounds	Favorite Song	-0.2923	-0.7403	0.1557	0.1779	34	-1.643	.110

Note. P-value and confidence intervals adjusted for comparing a family of 3 estimates (confidence intervals corrected using the Bonferroni method).

Post Hoc Tests

Math

Post Hoc Comparisons - Audio

			95% CI for Mean Difference					
		Mean Difference	Lower	Upper	SE	df	t	P_{Holm}
Silence	Nature Sounds	10.64	0.1659	21.11	4.158	34	2.558	.045
	Favorite Song	11.44	-1.882	24.77	5.291	34	2.163	.075
Nature Sounds	Favorite Song	0.8057	-8.307	9.919	3.619	34	0.2227	.825

Note. P-value and confidence intervals adjusted for comparing a family of 3 estimates (confidence intervals corrected using the Bonferroni method).

3B-C: These tables show Holm-corrected results for the Stroop and mathematical tasks at a 95% confidence interval. For the Stroop test, the p-values' significance did not change, and confidence intervals included or excluded 0 accordingly. However, for the mathematical test, results remained significant for nature sounds compared to silence, but significance was weaker (p_{Holm} = 0.045, CI[0.166, 21.11]). Additionally, the p-value increased to the point where it was not significant for preferred songs compared to silence, with the confidence interval containing 0 (p_{Holm} = 0.075, CI[-8.307, 9.919]).

Paired Samples T-Test

Paired Samples T-Test

								95% CI for Cohen's d	
Measure 1		Measure 2	t	df	p	Cohen's d	SE Cohen's d	Lower	Upper
HR Before	-	HR After	2.756	34	.009	0.4658	0.1485	0.1136	0.8119
Systolic BP Before	-	Systolic BP After	0.5840	34	.563	0.09871	0.1843	−0.2341	0.4301
Diastolic BP Before	-	Diastolic BP After	−0.4857	34	.630	−0.08209	0.1653	−0.4134	0.2504

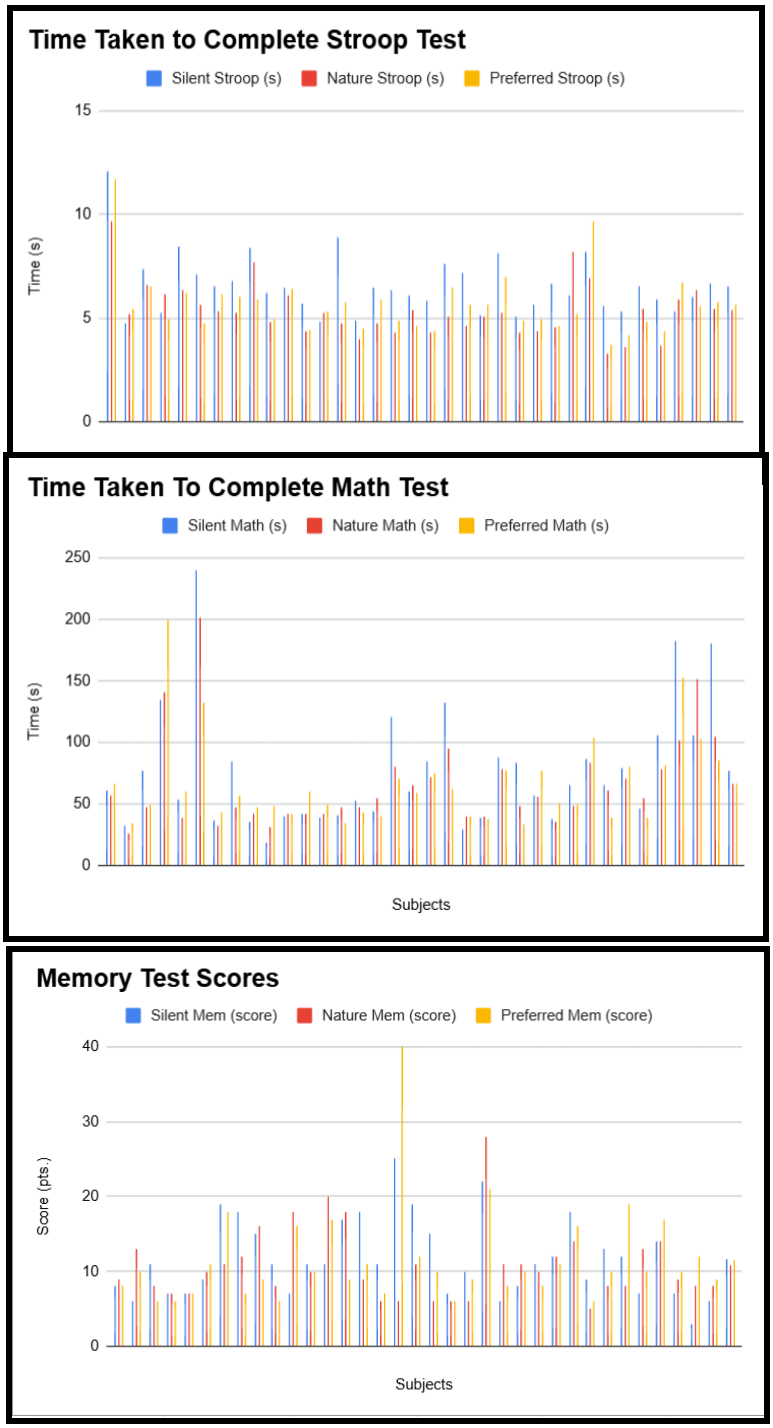
Note. Student's t-test.

3D: This table shows the pairwise t-tests regarding physiology before and after audio exposure. Participants' heart rates differed significantly (p = 0.009, 95% CI [0.1136, 0.8119]), but there were no such differences for either blood pressure metric.

Heart Rate p_{Holm}-value	Systolic Blood Pressure p_{Holm}-value	Diastolic Blood Pressure p_{Holm}-value
p_{Holm} = 0.027	p_{Holm} = 1.000	p_{Holm} = 0.630

3E: This table shows the Holm correction's results for physiology. None of these measurements differed substantially in significance; participants' heart rate changes remained significant.

Figure 4: Individual Performance Graphs



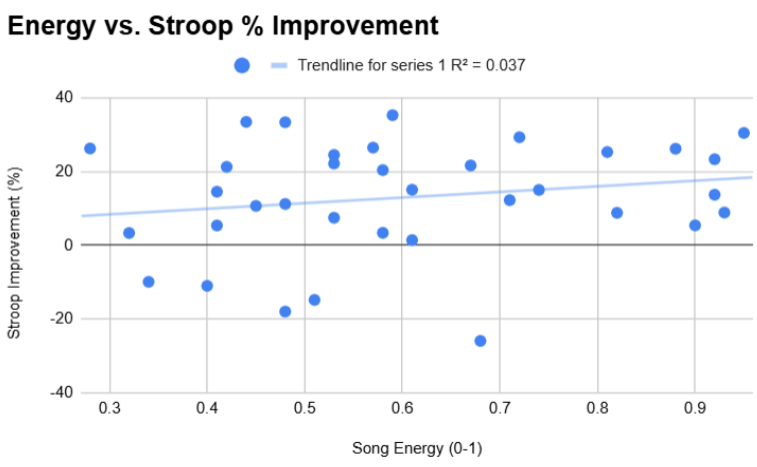
4A-C: These graphs show performance times and scores for all 35 test subjects. Performance varied clearly among all participants.

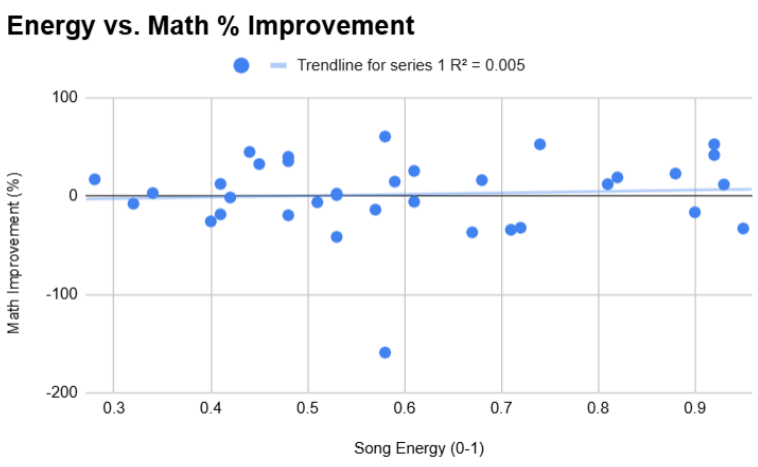
Figure 5: Favorite Song List

Participant	Song	Artist	Energy
1	Beqarar Karke Humein	Hemant Kumar	0.32
2	Reminder	The Weeknd	0.51
3	Role Model	Brent Faiyaz	0.48
4	Wild Horses	The Rolling Stones	0.41
5	Over My Dead Body	Drake	0.57
6	Kitchen	SZA	0.44
7	Memories	David Guetta	0.9
8	Forever Yours	Brent Faiyaz	0.45
9	20 Min	Lil Uzi Vert	0.72
10	Passion	PinkPantheress	0.58
11	Devil in a New Dress	Kanye West	0.61
12	Shabang	Drake	0.53
13	Nights	Frank Ocean	0.4
14	The Chain	Fleetwood Mac	0.59
15	ILoveUIHateU	Playboi Carti	0.82
16	Scenes from an Italian Restaurant	Billy Joel	0.93
17	Mr. Brightside	The Killers	0.92
18	I'd Rather Pretend	Bryant Barnes	0.53
19	Sweater Weather	The Neighbourhood	0.81
20	drop dead	Olivia Rodrigo	0.74
21	A Lonely Night	The Weeknd	0.67
22	Last Midnight	Meryl Streep	0.34
23	White Blank Page	Mumford & Sons	0.41
24	Classic	Drake	0.58
25	stupid song	Olivia Rodrigo	0.71
26	Freaks	Surf Curse	0.95
27	Hotel California	Eagles	0.61
28	Moonlight on the River	Mac DeMarco	0.48
29	SLOW DANCING IN THE DARK	Joji	0.48
30	El Paso	Marty Robbins	0.42
31	Morning Smiles	Marshall Giles	0.28
32	Balada	Gusttavo Lima	0.88
33	Black	Pearl Jam	0.68
34	Affection	BETWEEN FRIENDS	0.53
35	I Want You Back	The Jackson 5	0.92

5: This table displays a list of all songs chosen by participants to listen to during the preferred music portion of the study. Energy levels on the right match those from the Spotify API database. Subjects chose a wide range of preferred music. While some subjects chose extremely energetic songs/artists, others chose mellow and easygoing music.

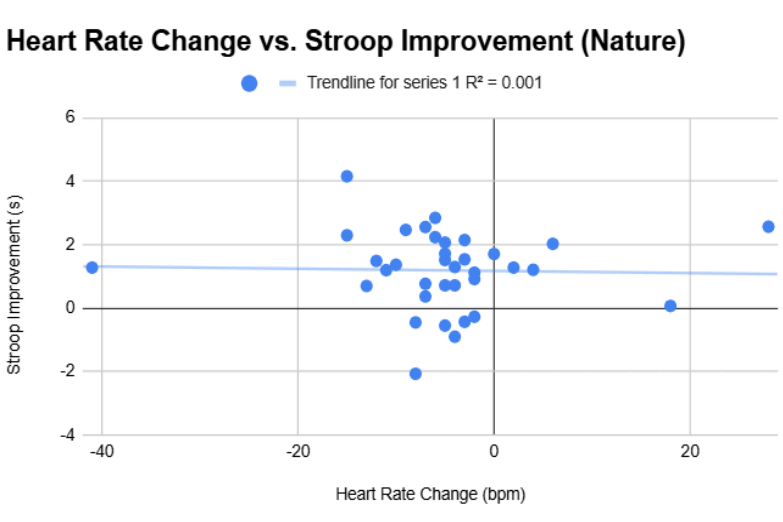
Figure 6: Energy Correlation Tests

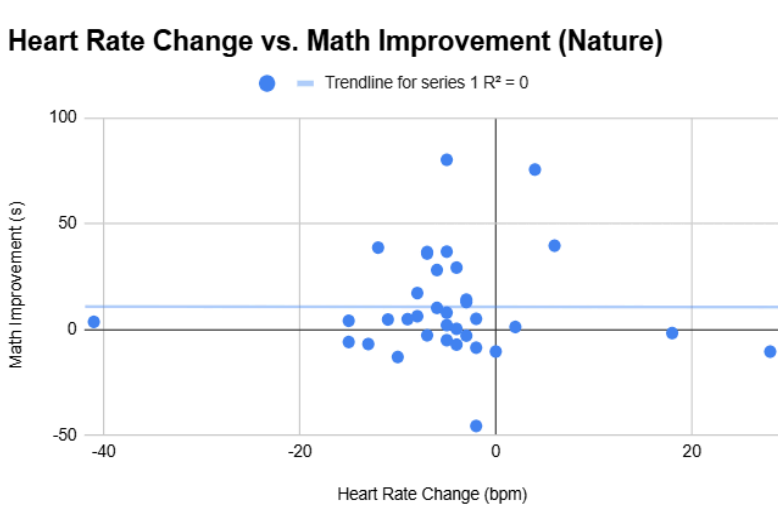


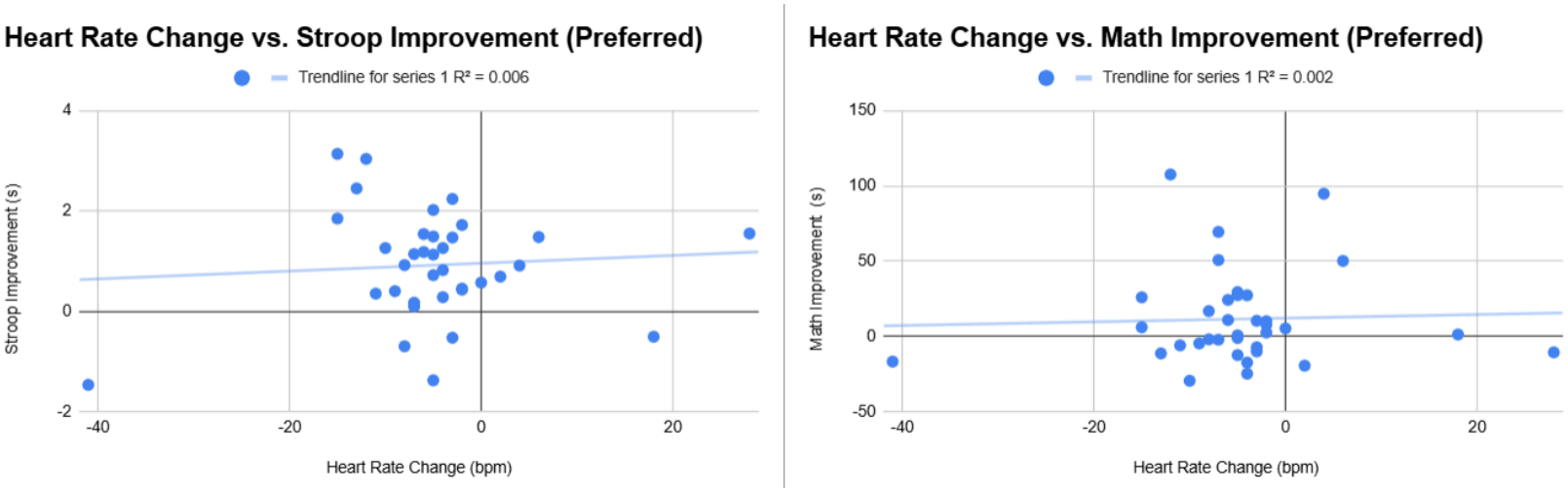


$$y - axis: \frac{(S-M)}{S} \times 100, \quad x - axis: Spotify\ API\ Energy\ Levels$$

6A-B: Pearson correlation between Spotify song energy and the percent change in cognition following exposure to preferred music. Percent change was calculated as $\frac{(S-M)}{S} \times 100$, where S represents silence performance, and M represents music performance. No significant trend emerged between song energy and test improvement, with R^2 values of 0.037 for the Stroop task and 0.005 for the mathematics task.







$$y - axis\text{: } \Delta Performance = Silence - Audio, \quad x - axis\text{: } \Delta HR$$

6C-F: Pearson correlation between changes in heart rate and changes on the Stroop and mathematics tasks following exposure to each audio cue. Changes in performance were calculated by subtracting the audio-influenced time from the silent time, and ΔHR represented heart rate changes. Most subjects who experienced a decrease in heart rate improved their performance. Nevertheless, the correlations between the magnitude of heart rate change and cognitive improvement were extremely weak, with R^2 values of 0.001 (preferred music) and 0.006 (nature sounds) for the Stroop task, and $R^2 < 0.001$ (preferred music) and 0.002 (nature sounds) for the mathematics task.

DISCUSSION

Cognitive Performance

This proof-of-concept study tested the hypothesis that auditory stimuli could improve cognitive ability and physiology in adolescents. The results indicate that, relative to those who listened to silence, participants who listened to audio cues performed significantly better in cognitive flexibility and mathematical ability, with slightly better performance under nature sounds than preferred music (Fig. 1A, 2A-B, & 3A-C). The lack of a significant difference in mathematical performance under silence and preferred music could be attributed to linguistically demanding questions. A previous study determined that language skills were strongly correlated with linguistically demanding problems, such as word problems (Amland et al., 2025). Thus, the lyrical content of preferred songs may have competed with the linguistic content of the problems during testing, potentially nullifying the cognitive benefits of preferred music.

Past studies have shown that sound cues activate the auditory cortex, engage cortical networks involving the prefrontal and parietal cortices, and facilitate executive processing (Davidson & Souza, 2023). Subjects' relative improvement for the first two tests may support this notion, though brain activity was not directly measured. On the other hand, no such correlation appears to exist between auditory stimuli and short-term memory (Fig. 1A & 2C). Since sequence memory relies on hippocampal networks, the memory test's varied findings may suggest that brief audio exposure may not have a definitive effect on these networks. Nevertheless, research directly measuring neural activity is necessary to confirm this proposal. Overall, the results indicate that auditory stimuli appear to be effective when addressing specific cognitive aspects in adolescents, yet may have little relevance to others, as the null results from the memory test indicate (Fig. 2C).

Cognitive performances followed a general trend of nature performance ≥ preferred performance ≥ silence performance for the first two tests commonly enough that order as a variable didn't appear to offset the trend between separate auditory stimuli, so test order wasn't considered in this specific regard to maintain the study's focus on performance under different auditory stimuli. Mathematical performance trends were much more tentative than Stroop performances (Fig. 1A & 4). However, it may be possible that experience, with even one or two passes, could affect the variation of cognitive improvement. Thus, larger-scale studies should explore the potential effects of test order on performance.

Future research should also investigate other forms of cognition (e.g., spatial reasoning) to determine if auditory stimuli can benefit them. This is because exposure to music can already enhance verbal memory (Musacchia et al., 2007). To broaden these cognitive benefits, studies should also endeavor to find specific forms of auditory stimuli that provide the optimal cognitive benefits for each skill.

Physiological Performance

Some physiological aspects may be much more responsive to auditory stimuli than others, as heart rate decreased by an average of about 5 bpm by the end of the sessions (Fig. 1B & 3D) despite insignificant changes in blood pressure. However, since participants experienced multiple auditory conditions during sessions, this decrease cannot necessarily be attributed to a specific audio cue. Future research can examine the individual effects of auditory stimuli on these physiological biomarkers. The weak relationship between heart rate impact and improvement on the tests (Fig. 6C-F) may suggest that while reduced heart rate commonly accompanied improved performance, it did not strongly predict the magnitude of cognitive improvement. Nevertheless, the lack of a significant difference between performance and systolic or diastolic blood pressure (Fig. 3D-E) suggests that stress responses following auditory stimuli may be selective.

The improvement on the first two tests after listening to preferred music supports the arousal-mood hypothesis. For nature sounds, a different mechanism may be at work. Nature sounds have been associated with decreased skin conductance level (Alvarsson, 2010) and increased HRV (Goulding et al., 2017), reflecting sympathetic nervous system (SNS) deactivation and an increase in the parasympathetic nervous system's (PNS) activity. While this study did not measure these attributes, previous works

(Alvarsson, 2010; Goulding et al., 2017) showed that such changes may preserve attentional resources available for executive processing by reducing autonomic stress. Given the participants' general improvements, this experiment's findings support this physiological process. Still, parasympathetic activity should be specifically explored, as it was not directly measured. However, baseline stress levels are also important to note, as one study found that differences in cognitive performance occur when parasympathetic activity was relatively low before audio exposure (Goulding et al., 2017). This is why the study's tests were relatively straightforward; unfamiliarity and difficulty during the tests may have spiked participants' heart rates due to stress. Even so, this study's subjects' improved performances cannot be definitively attributed to larger changes in heart rate given the weak correlations between them (Fig. 6C-F).

Audio Cues' Diversity

Specific genres may not universally improve cognitive performance. The sporadic improvements from preferred music (Fig. 4) were initially thought to be due to the songs' energy levels. This is because different musical genres, such as rock, can produce varying P3 amplitudes, which in turn reflect varying cognitive levels (Schellenberg, 2012). However, given the weak correlation between song energy and performance on the first two tests, preferred music potentially benefited cognitive abilities regardless of its energy (Fig. 6A-C). These results are inconsistent with the Mozart effect (Nantais & Schellenberg, 1999) but, as stated above, align with the arousal-mood hypothesis. Given that preferred music should make one feel better, its positive arousal can potentially offset the effects of distracting cues and still enhance cognition, but this notion should be evaluated more rigorously.

Additionally, elements of preferred music beyond energy (e.g., rhythm, lyrical content, mood) may support cognition, but this requires additional investigation. Noise familiarity may also be worth exploring. Unfamiliar auditory stimuli capture attention and can be more distracting than preferred music, whose predictability can require less attention.

These results may also suggest that adolescents' cognitive flexibility and mathematical skills improve most from calm, non-lyrical stimuli such as nature sounds. Although there was no significant difference between the two audio groups (Fig. 3A-B), participants usually performed best following nature sounds (Fig. 1A). As a preliminary study, these findings may potentially propose that attentional demands are minimized after exposure to nature sounds, possibly by preserving cognitive capacity more efficiently than the dopaminergic effects of preferred music. However, future studies are needed to establish the extent of these findings.

Comparative Studies

These findings regarding cognition are consistent with those of Nobuo Masataka and Leonid Perlovsky (Masataka & Perlovsky, 2012). The Stroop (color) Test deliberately gives conflicting information to the occipital lobe (which gauges color) and the temporal lobe (which gives meaning to words), testing the PFC's decision-making. Subjects' ability to make correct decisions faster following auditory stimuli supported the notion that music efficiently buffers such cognitive dissonance. The observed decrease in

heart rate is also supported by Wendy E. J. Knight and Nikki S. Richard, who show that music tends to buffer against increases in heart rate under stressful conditions, such as during tests (Knight & Richard, 2001). Moreover, this study's findings support research by Valentin Magnon. She found that higher vagally mediated heart rate variability resulted in improved cognitive flexibility and inhibition, but she saw no correlation with working memory (Magnon et al., 2022). Thus, although this study did not measure vagally mediated heart rate, the cognitive results could be seen as an extension of Magnon's study toward adolescents.

Conversely, this experiment's results do not seem to align with Zhong Jian Chee's. Her study claims that ambient noise can decrease cognitive function in adults (Chee, 2024). However, "ambient noise" in this paper refers to unnatural sounds associated with environmental pollutants. Another study found that subjects recovered from stress faster under nature sounds than urban noise, highlighting nature sounds' superiority in promoting cognition, perhaps because such sounds convey environmental nonpollutants (Alvarsson et al., 2010). Nevertheless, both of these auditory stimuli are nonlyrical and nonrhythmic. Thus, associations between such sounds and cognition are probably not universal.

Limitations

This study's results should be examined in light of their limitations. The data did not fully account for participants' music experience for generalization to all adolescents. Music training is associated with improvement on some cognitive tasks, but it is unlikely to find a substantial number of adolescents having the same experience with music. Baseline mood and stress levels, which could not be accurately measured, may have affected subjects' physiological responses and their performance. Also, the sample size is too small to generalize to all adolescents (Fig. 4). There was also no control for external factors, such as sleep or caffeine. Additionally, the variation in the times of day when sessions were held may have contributed to variability in the results. Although decreases in heart rate were commonly observed regardless of testing times, circadian variation could modulate brain activity and alertness on a small scale (Valdez et al., 2012). While the mathematical tests were generalized in difficulty for every subject, prior exposure to the other two cognitive tests could have played a minor role in performance. The participants generally appeared unfamiliar with these tests, and they were simple enough to understand during the first trials, but these facts do not fully eliminate this variable of familiarity. Because each participant selected their preferred songs, familiarity with each song could not be controlled. Some participants may have recently discovered their song and been less familiar than others. Furthermore, individual preference between nature sounds and lyrical music was not measured, as results for each auditory group required distinction. While this study's trends are mostly consistent with existing literature, the smaller sample size suggests a need for larger-scale research to improve the findings' precision and generalizability.

CONCLUSION

Based on this preliminary study, exposure to auditory stimuli may potentially benefit adolescents' cognition while mitigating physiological stress responses. Although music training has been associated with intelligence, audio exposure's cognitive boosts may still be accessible to those who haven't had the same experience. The results of this study may point toward cognitive benefits of auditory stimuli, so future projects should measure their neurological effects in students under test-induced stress. Larger samples, more cognitive tasks, and controlled experimental settings will be necessary to establish generalizability across all adolescents. Future research should investigate whether these brief improvements can be sustained in the long term, supporting adolescents with cognitively demanding work they encounter.

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