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Effects of Theta (6 Hz), Beta (15 Hz), and Gamma (40 Hz) Binaural Beat Stimulation on Adolescents' Reaction Time

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Abstract

Binaural beat auditory stimulation has been proposed as a non-invasive method for modulating cognitive processes. This experimental study investigates whether binaural beat frequency exposure influences reaction time in adolescents aged 15–16. Reaction time is closely associated with attention, sensory processing, and sensory-to-motor coordination, all of which undergo significant development during adolescence due to synaptic pruning and increased myelination, which may enhance neural responsiveness to auditory stimulation. Previous electroencephalography (EEG) studies suggest that binaural beats can influence neural oscillations associated with attention and cognitive performance. Ten adolescents aged 15–16 (n = 10) were exposed to binaural beats at theta (6 Hz), beta (15 Hz), and gamma (40 Hz) frequencies, alongside a silent control condition to establish a baseline. Results showed an overall negative relationship between binaural beat frequency and reaction time, with higher frequencies associated with faster sensory-motor responses. Mean reaction time decreased from 283.63 ms in the theta condition to 250.92 ms in the gamma condition, with the control condition (no external auditory stimulus) showing a mean of 264.00 ms. Individual variability increased at higher frequencies, which may reflect differences in neural sensitivity. Correlation analysis indicated a strong negative relationship between frequency and reaction time ($r \approx -0.91$). However, this correlation should be interpreted with caution, as it is based on a limited number of discrete frequency conditions rather than continuous data. Overall, these findings suggest that auditory frequency exposure may influence cognitive performance in adolescents and highlight the potential of low-cost auditory stimulation methods for improving attention and sensory-motor responsiveness in educational and training environments. However, further research with larger sample sizes is required to confirm this relationship.

Keywords
Binaural beats, auditory stimulation, neural oscillations, reaction time, cognitive performance.

1. Introduction
During adolescence, the brain undergoes major structural and functional changes that influence cognitive processing, attention, and sensory-motor responsiveness. These developmental processes strengthen connections within neural networks and improve the processing of information related to attention and cognition, including responses to environmental stimuli. However, gray matter volume decreases due to synaptic pruning, a process in which the weaker neural connections are eliminated to improve information-processing efficiency. Simultaneously, white matter increases through myelination, as axons become more myelinated, allowing for faster transmission of nerve impulses between brain regions. Such structural and functional changes indicate that neural circuits involved in attention and cognition are still developing. Therefore, adolescence represents an ideal stage to investigate how binaural beats may influence reaction time.

Binaural beats are auditory stimuli created by presenting two tones of slightly different frequencies separately to each ear. As a result, the brain perceives a third rhythmic beat corresponding to the frequency difference between the two tones. The brain's electrical activity, measured using electroencephalography (EEG), may synchronize with this perceived beat frequency, resulting in a process known as brainwave entrainment. EEG measures and records the electrical impulses produced by neurons in the brain through detecting tiny voltage fluctuations, mapping brain wave patterns (Cleveland Clinic 2025). Through this process, the brain may shift toward a corresponding cognitive state, such as relaxation (theta ≈ 6 Hz) or increased focus (gamma ≈ 40 Hz). Different frequency ranges correspond to different cognitive states; for example, beta-frequency binaural beats (15 Hz) have been shown to enhance attention and reaction time by aligning with the brain's naturally occurring beta rhythms, as suggested by Beauchene et al. (2016).

Rather than acting through neurotransmitter release (a biochemical mechanism), binaural beats are believed to influence cognition by modulating neural oscillations. Aligning brain activity with higher frequency oscillations (e.g., beta or gamma) may promote more efficient communication between sensory and motor pathways, supporting quicker detection of stimuli and therefore faster reaction times. Neural oscillations influence the efficiency of incoming information, and research in neurophysiology indicates that the time of sensory processing depends on the phase of ongoing brain rhythms. In the alpha range, where cortical excitability naturally fluctuates (8–13 Hz), stimuli that arrive during low-excitability phases may be processed more slowly, producing longer reaction times. In contrast, faster oscillatory activity, such as beta and gamma rhythms (15 Hz and 40 Hz), produces more frequent peaks in cortical excitability, supporting quicker sensorimotor coordination and reduced reaction time (Lansing 1969). Because adolescents are undergoing synaptic pruning and neural rewiring, their neural oscillatory networks may be particularly responsive to external rhythmic stimulation.

1.1 Objectives

Reaction time is widely used in cognitive neuroscience as an indicator of sensory processing speed and efficiency of communication between sensory and motor brain regions. It is hypothesized that higher-frequency binaural beats (beta and gamma) would result in faster reaction times compared to theta and control conditions. Investigating whether these frequencies influence adolescent reaction time provides insight into real-life contexts, as it allows for a better understanding into how auditory stimulation interacts with the developing nervous system. Understanding this relationship may have potential real-world applications, particularly in fields such as education. If certain binaural frequencies are shown to improve focus, attention, or responsiveness, they may be adapted within everyday environments to support cognitive performance. In educational settings, such auditory stimulation may support learning efficiency, while in physical or health-related contexts improved sensorimotor processing may enhance performance in tasks requiring rapid responses. Furthermore, such findings contribute to a broader understanding of adolescent brain activity, which may inform the development of future technologies aimed at improving cognitive function and attention regulation. Therefore, understanding how binaural beat frequency influences reaction time provides a foundation for the present investigation.

2. Literature Review

Previous research indicates that binaural beat stimulation can influence cognitive processes such as attention, memory, and concentration by modulating neural oscillatory activity through the entrainment of brain rhythms. When two tones of slightly different frequencies are presented separately to each ear, the auditory system perceives a third rhythmic beat corresponding to the difference between the frequencies. This perceived beat can modulate neural activity in the auditory cortex and associated neural networks (Orozco-Perez et al. 2020; Chaieb et al. 2015). Studies using electroencephalography (EEG) have shown that binaural beats may influence psychological and cognitive processes, including attention, vigilance and reaction time, as reported by Lane et al. (1998).

Under resting conditions, the brain predominantly operates within the alpha frequency range (8–13 Hz), which is associated with stable sensory processing and cognitive function, as described by Klimesch (1999). However, fluctuations in neural oscillatory activity influence responsiveness to environmental stimuli, contributing to variability in reaction-time performance. Auditory stimulation through binaural beats may provide a controlled method of influencing neural activity by entraining brain oscillations toward specific frequencies. This process, known as neural entrainment, occurs when external rhythmic stimuli synchronize with ongoing neural activity in the brain (Herrmann et al. 2010). Through this process, binaural beats may alter cognitive states such as relaxation, concentration, and alertness depending on the frequency of the stimuli.

Theta-frequency oscillations (approximately 4–7 Hz) are generally associated with low-arousal brain states, internally focused cognition and reduced attentional vigilance. EEG studies have associated increased theta activity with reduced sensory processing and alertness, as reported by Klimesch (1999) and Lansing (1969). Because reaction time is dependent on rapid detection of external stimuli and efficient coordination between sensory and motor pathways, increased theta activity may reduce the speed of sensory-motor processing. Therefore, adolescents exposed to theta-frequency binaural beat (6 Hz) are expected to demonstrate longer reaction times relative to other experimental conditions.

In contrast, beta-frequency oscillations (approximately 12-30 Hz) are commonly associated with active concentration, alertness and motor control. Beta activity supports enhanced communication between cortical regions involved in attention and sensory-motor processing through improved oscillatory synchronization (Beauchene et al. 2016; Thut et al. 2012). Auditory entrainment through beta-frequency binaural beats may therefore result in improved efficiency of neural communication between sensory and motor regions. As a result, adolescents exposed to beta-frequency stimulation (15 Hz) are expected to demonstrate faster reaction times compared to the theta condition.

Gamma-frequency oscillations (approximately 30-50 Hz) are associated with high-level cognitive processing and rapid neural synchronization, supporting intense attentional focus across distributed neural networks, as demonstrated by Herrmann et al. (2010). Increased gamma activity has been observed during tasks involving sensory processing and attentional control, suggesting that this frequency condition plays an important role in neural communication between brain regions. These oscillations reflect the synchronization of neuronal assemblies across cortical networks, enabling efficient communication between brain regions during complex cognitive tasks (Jensen et al. 2007).

A control group with no auditory stimulation is essential to establish a baseline for comparison, allowing for more reliable interpretation of the results. It is expected that the control group will produce moderate reaction times, reflecting the brain's natural neural activity in the absence of externally induced entrainment.

More recent research continues to support the potential cognitive effects of binaural beat frequency. However, findings remain mixed across studies. A study by Kahathuduwa et al. (2025) demonstrated that EEG-guided binaural beats significantly improved reaction time and aspects of executive function, suggesting that auditory entrainment has the potential to enhance cognitive performance under controlled conditions.

In summary, previous research suggests that neural oscillations play an important role in sensory processing and cognitive performance. Lower-frequency oscillations such as theta may reduce attentional vigilance and slow sensory processing, whereas higher-frequency oscillations such as beta and gamma are associated with increased cortical excitability and improved sensory-motor responsiveness.

Given that binaural beat stimulation may influence neural oscillations through auditory entrainment, increasing binaural beat frequency is predicted to reduce reaction time. Consequently, adolescents exposed to theta-frequencies (6 Hz) are expected to display the longest reaction times, while those exposed to beta and gamma frequencies are expected to demonstrate progressively faster responses. Overall, this suggests a negative relationship between binaural beat frequency and reaction time in adolescents.

3. Methods

Based on these findings, an experimental approach was designed to investigate the relationship between binaural beat frequency and adolescent reaction time. This study used a within-subjects experimental design, where each participant completed reaction-time trials under four auditory conditions; control (no additional stimulus), theta (6 Hz), beta (15 Hz) and gamma (40 Hz). The order of conditions was kept consistent for all participants, introducing a systematic confounding variable. However, this may have resulted in order effects such as practice-related improvement or fatigue, thereby reducing the internal validity of the investigation.

3.1 Control and preparation of investigation

A total of 10 participants aged 15-16 were recruited to allow comparison across individuals. Participants were instructed to avoid caffeine for at least 12 hours prior to the experiment and to use their dominant hand during the reaction-time task.

Each participant was seated individually in a controlled environment where lighting was moderate and auditory distractions were minimized. Additionally, a fixed distance was maintained between participants' hand and device to ensure consistent testing conditions.

3.2 Baseline measurement

Each participant was provided the same model of stereo headphones, playing no audio (silent control). The reaction-time test was opened on the same device for all participants to minimize external influences unrelated to binaural beat stimulation. Participants were instructed to follow the instructions provided by the online reaction-time test (https://humanbenchmark.com/tests/reactiontime) and press the response key as quickly as possible when the visual stimulus appeared. All individual reaction times were recorded in milliseconds (ms) in a digital spreadsheet for later data analysis. Each participant completed five trials under the silent control condition. If a participant became distracted and an extreme outlier was recorded, the trial was repeated.

3.3 Theta conditions (6 Hz)

The 6 Hz theta-frequency binaural beat was played through the same headphones at a fixed volume of 80 dB. Participants were allowed a one-minute break, then exposed to the auditory stimulus for thirty seconds prior to testing to allow time for auditory adjustment. The reaction-time was then conducted while the binaural beat played continuously. Each participant completed five trials under the theta condition, and all reaction times were recorded in milliseconds.

3.4 Beta conditions (15 Hz)

After completing the theta trials, participants were given a one-minute break while the audio file was changed to the beta-frequency binaural beat (15 Hz) at the same volume (80 dB). Participants completed five reaction-time trials while the beta-frequency stimulation played continuously, and all reaction-time data were recorded individually in milliseconds in the digital spreadsheet.

3.5 Gamma condition (40 Hz)

Following the beta condition, participants were given another one-minute break before the audio file was changed to the gamma-frequency condition (40 Hz), maintaining the same volume level (80 dB). Participants completed the reaction-time test while the gamma-frequency stimulation played continuously. Each participant completed five trials under the gamma condition, and all reaction times were recorded in milliseconds in the digital spreadsheet. After completing all conditions for one participant, the same procedure was repeated for all remaining participants ($n = 10$).

Reaction-time data were analyzed using both descriptive and inferential statistical methods. All statistical analyses were conducted using standard parametric approaches, assuming normal distribution of reaction-time data. Mean reaction times and standard deviations were calculated for each auditory condition. A Pearson correlation analysis was conducted to examine the relationship between binaural beat frequency and reaction time. Additionally, a paired-samples t-test was used to compare the theta (6 Hz) and gamma (40 Hz) conditions in order to evaluate whether the observed difference in reaction time was statistically significant. Lastly, effect size was calculated using Cohen's d to estimate the magnitude of the observed difference.

Ethical considerations

Participants were informed that they could withdraw from the investigation at any time without penalty. Participants were aged 15-16, all collected data remained anonymous. Short breaks between conditions were provided to reduce fatigue and potential auditory strain from headphone use. Audio volume did not exceed 80 dB, ensuring that sound levels remained within safe listening limits.

4. Data Collection

Table 1 presents the individual reaction-time measurements recorded for each participant across all binaural beat frequency conditions. Overall, reaction times varied between participants, reflecting individual differences in baseline cognitive processing and responsiveness to auditory stimulation. A general trend is observed in which slower responses occurred under theta conditions, whereas faster responses occurred under higher-frequency conditions.

Table 1. Reaction Time Data (ms) for Each Participant Across All Binaural Beat Conditions at 80 dB

Frequency of binaural beat (Hz) at 80dB	Reaction time measured in ms (milliseconds)					Reaction time measured in ms (milliseconds)					Reaction time measured in ms (milliseconds)					Reaction time measured in ms (milliseconds)					Reaction time measured in ms (milliseconds)				
	Adolescent 1					Adolescent 2					Adolescent 3					Adolescent 4					Adolescent 5				
Theta (6 Hz)	411	252	276	260	290	269	240	323	229	252	262	216	218	235	226	263	235	229	241	241	428	355	361	277	389
Control	222	273	270	258	251	234	228	235	260	238	230	266	235	224	238	259	260	245	282	250	380	282	309	411	376
Beta (15 Hz)	240	240	275	257	221	248	241	244	257	240	241	241	244	257	240	271	265	264	256	231	478	289	352	341	304
Gamma (40 Hz)	225	248	264	249	251	257	248	282	232	508	239	239	229	218	221	249	248	238	255	246	342	429	333	451	321

Reaction time measured in ms (milliseconds)					Reaction time measured in ms (milliseconds)					Reaction time measured in ms (milliseconds)					Reaction time measured in ms (milliseconds)					Reaction time measured in ms (milliseconds)						
Adolescent 6					Adolescent 7					Adolescent 8					Adolescent 9					Adolescent 10					MEAN	STDEV
286	205	217	204	230	295	278	310	260	288	320	305	295	330	310	285	300	290	275	295	340	325	310	330	320	283,62	51,24
216	236	199	317	235	250	242	268	255	260	275	260	268	255	262	260	255	270	265	258	285	270	275	280	268	264,00	38,47
284	311	199	224	250	232	240	225	238	230	245	238	250	240	235	235	242	230	238	240	255	245	250	248	242	256,06	41,99
261	210	208	207	219	215	222	210	218	220	225	218	220	230	215	220	215	225	218	210	230	225	235	220	228	250,92	62,00

Table 2. Mean Reaction Time (ms) and Standard Deviation Across All Binaural Beat Conditions at 80 dB

Frequency of binaural beat (Hz) at 80dB	Mean. Average	STDEV
Theta (6 Hz)	283.63	51.24
Control	264.00	38.47
Beta (15 Hz)	256.06	41.99
Gamma (40 Hz)	250.92	62.00

Table 2 summarizes the experimental results, showing the mean reaction time and standard deviation for each experimental condition. The theta condition (6 Hz) produced the slowest mean reaction time, whereas the gamma condition (40 Hz) resulted in the fastest average response.

In addition, variability increased across conditions, with the standard deviation rising from 51.24 ms in the theta condition to 62.00 ms in the gamma condition. This suggests that individual differences in neural responsiveness are more amplified in higher-frequency stimulation. Moreover, under the control condition, reaction time produced the smallest variability (SD = 38.47).

Table 3. Statistical Comparison of Reaction Times Between Binaural Beat Frequency Conditions

Comparison	Mean Difference (ms)	t-value	df	p-value	Effect Size (Cohen's d)	Interpretation
Theta (6 Hz) vs Gamma (40 Hz)	32.71	1.29	18	0.21	0.57	Moderate effect, not statistically significant
Theta (6 Hz) vs Beta (15 Hz)	27.57	1.33	18	0.2	0.54	Moderate effect
Control vs Gamma (40 Hz)	13.08	0.63	18	0.53	0.24	Small effect

Table 3 presents the statistical comparison between different auditory conditions. For instance, the results from theta (6 Hz) vs Gamma (40 Hz) indicated the mean reaction time difference was 32.71 ms, although the t-test result was not statistically significant ($p = 0.21$), the effect size (Cohen's $d = 0.57$) indicates a moderate practical effect.

5. Results and Discussion

This investigation aimed to determine whether binaural beat frequency influences adolescent reaction time. Analysis of the processed data shows an overall trend in which increasing binaural beat frequency was associated with a decrease in mean reaction time. As shown in Figure 1, the theta condition (6 Hz) produced the slowest mean reaction time (283.63 ms), while the gamma condition (40 Hz) produced the fastest mean reaction time (250.92 ms). In comparison, the beta condition (15 Hz) produced a mean reaction time of 256.06 ms and control (264.00 ms) conditions displayed intermediate values.

Overall, the reduction in the mean reaction-time between theta and gamma conditions (32.7 ms) suggests a negative relationship between binaural frequencies and reaction times. A correlation analysis between binaural beat frequency and mean reaction time showed a strong negative relationship ($r \approx -0.91$), further supporting the trend that higher auditory frequencies are associated with faster response times. These findings are supported by recent research which indicates that binaural beat stimulation can influence cognitive performance through neural entrainment. For instance, Mujib et al. (2026), using electroencephalography (EEG) and graph-theoretical analysis, demonstrated that binaural beats may alter brain network efficiency, potentially enhancing working memory performance. Nevertheless, recent studies also highlight that the effects of binaural beats are not universally consistent and depend on individual neural sensitivity and experimental design.

To further evaluate this trend, a paired-samples t-test comparing the theta (6 Hz) and gamma (40 Hz) conditions was conducted. The results indicated a mean difference of 32.71 ms, however the difference was not statistically significant ($t(18) = 1.19$, $p = 0.21$). The small sample size ($n = 10$) reduces statistical power and increases the likelihood of errors, limiting the ability to detect statistically significant differences. Despite not reaching statistical significance, the effect size was moderate (Cohen's $d = 0.57$), suggesting that higher-frequency binaural beats may still have a meaningful influence on sensorimotor response speed.

Further comparison between the conditions shows that the beta condition resulted in a reaction time approximately 7.9 ms faster than the control, suggesting that exposure to binaural beats at mid-range frequencies may still have an impact on performance compared to no auditory stimulation. The control condition produced intermediate reaction times, suggesting a moderate baseline level of performance in the absence of binaural beat stimulation.

Variability differed between conditions. As shown in Figure 1, the error bars representing standard deviation values indicate that the control condition exhibited the lowest variability (SD = 38.47). This suggests that participant responses were relatively consistent when no auditory stimulation was present.

In contrast, all binaural beat conditions showed higher variability between participants. The beta condition showed moderate variability (SD = 41.99 ms), while the theta condition showed increased variability (SD = 51.24 ms). Nevertheless, the gamma conditions (40 Hz) in particular exhibited the greatest standard deviation (SD = 62.00 ms), suggesting that individual differences in sensitivity to binaural beat stimulation influenced response, particularly at higher frequencies. Variations in response may reflect differences in neural entrainment, as not all individual brain oscillations synchronize to external auditory frequencies with equal effectiveness.

Previous research suggests that rhythmic sensory stimulation can entrain neural oscillations within the brain, influencing cognitive processing and behavioral performance, as reported by Herrmann et al. (2010) and Orozco-Perez et al. (2020). In particular, gamma oscillations have been associated with enhanced attentional processing and faster sensory-motor responses, as they facilitate rapid communication between distributed cortical networks, as suggested by Jensen et al. (2007).

This increased variability observed in the gamma condition therefore indicates, while higher-frequency stimulation may improve reaction time on average, the degree of neural synchronization with external auditory stimuli varies between individuals. Such individual differences may influence the effectiveness of binaural beats in modulating cognitive performance.

In conclusion, exposure to higher-frequency binaural beats was associated with faster reaction times on average, with the gamma condition (40 Hz) producing the fastest reaction time (250.92 ms). Although statistical significance was not achieved due to the limited sample size, the moderate effect size and consistent downward trend in reaction time across increasing frequencies suggests that auditory frequency exposure may influence adolescent sensory-motor responses. This trend is consistent with previous research indicating that beta and gamma neural oscillations are associated with enhanced attentional processing, increased cortical activations and improved communication efficiency between sensory and motor brain regions, which may lead to faster responses, as suggested by Jensen et al. (2007), Thut et al. (2011), and Beauchene et al. (2016). These oscillatory rhythms are believed to support synchronized neural communication across cortical networks, improving the efficiency of sensory processing and motor response coordination. Increased oscillatory synchronization may improve the temporal coordination of neural processing between sensory and motor regions, allowing sensory information to be processed and translated into motor responses more efficiently.

5.1 Graphical Results

Figure 1 illustrates the relationship between binaural beat frequency and mean reaction time. The graph shows a downward trend as the frequency increases from 6 Hz to 40 Hz, indicating that higher-frequency auditory stimulation is associated with faster reaction times.

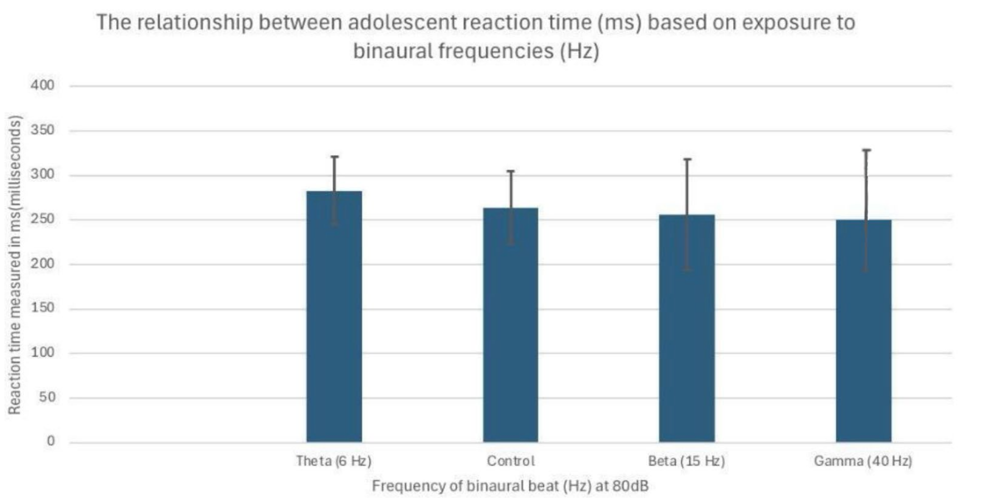

Figure 1. Relationship between binaural beat frequency and mean reaction time

The theta (6 Hz) condition appears as the highest point on the graph, while the gamma (40 Hz) represents the lowest mean reaction time. The control and beta conditions fall between these values, demonstrating a gradual reduction in reaction time as frequency increases.

Error bars in the figure represent the standard deviation for each condition. The gamma condition displays the largest error bars, reflecting greater variability amongst participants.

Overall, the graphical results support the negative relationship between binaural beat frequency and reaction time, supporting the trend observed in the numerical analysis.

5.2 Proposed Improvements

Several limitations should be considered when interpreting the results of this investigation. First, the sample size was relatively small (n = 10), which reduces statistical significance and limits the generalizability of results. Second, all participants completed auditory stimulation conditions in the same order, which may have introduced order effects such as learning or fatigue. Future studies should randomly select conditions to minimize this effect. Finally, the exposure duration was relatively short, which may not have allowed sufficient time for neural entrainment to occur.

The purpose of this investigation is to determine the effects of binaural beat frequencies on adolescents' reaction times; these findings may be useful for educational fields or further understanding of how adolescent brains respond to external auditory stimulation and may have potential applications in educational settings where attention and cognitive performance are important.

One possible improvement to this investigation would be the inclusion of heart rate monitoring during each binaural beat condition. Heart rate is regulated by the autonomic nervous system and may reflect psychological states such as stress, alertness and arousal. Measuring heart rate during the experiment would allow researchers to account for differences in participants' physical states that may influence reaction-time performance. For example, elevated heart rate may indicate increased alertness, while lower heart rates may reflect relaxation. By monitoring these changes, it would be easier to determine whether unusual reaction-time results were caused by binaural beat stimulation or by changes in physiological arousal. Including heart rate measurements could therefore improve the validity of the investigation by controlling for physiological variables, which may influence sensory-motor responses.

Another possible extension for this investigation would be to extend the duration of binaural beat exposure. In the present investigation, participants were exposed to binaural beats for a relatively short period before testing. However, neural adaptation and brainwave entrainment may become more effective with longer exposure. If this investigation were to be repeated, comparing reaction times with different listening durations (e.g., 30 seconds, 1 minute or 2 minutes) for each frequency. This would allow for proper analysis on which lengths are most efficient for adolescent neural entrainment. Through implementing longer durations of binaural beat exposure, the variability of this investigation may be reduced as it allows adolescents to adapt more to the auditory stimulus.

The final potential extension of this integration would be to examine whether longer durations of binaural beat exposure influence the individual sensitivity to binaural beats. Future studies could therefore investigate whether extended exposure periods lead to stronger neural entrainment and greater improvements in sensory-motor response speed. Additionally, repeated exposure across multiple experimental sessions could be examined to determine whether individuals gradually become more responsive to binaural beat stimulation over time. If neural entrainment strengthens with repeated stimulation, participants may demonstrate progressively faster reaction times as their brain activity becomes more synchronized with the auditory stimulus.

5.3 Validation

Statistical analysis was conducted to evaluate whether the observed relationship between binaural beat frequency and adolescent reaction time was supported by the experimental data. A correlation analysis indicates that the binaural beat frequency and reaction time produced a strong negative correlation ($r \approx -0.91$). This suggests that higher-frequency stimulation was generally associated with faster reaction times. This result supports the proposed prediction where increasing binaural beat frequency may improve sensory-motor response speed.

A t-test comparing the theta (6 Hz) and the gamma (40 Hz) conditions was also conducted to further evaluate the validity of statistical results. The analysis produced a mean difference of 32.71 ms, although the results were not statistically significant ($t(18) = 1.29$, $p = 0.21$). This lack of significance is likely influenced by the small sample size ($n = 10$). However, the calculated effect size (Cohen's $d = 0.57$) indicates a moderate practical effect, suggesting that binaural beat frequency may still have an influence on reaction-time performance. These findings are consistent with previous studies, which reported improved cognitive performance under higher-frequency stimulation.

Despite the overall trend observed in the dataset, variability between participants was relatively high, particularly at higher binaural frequencies (gamma-frequency condition). This variability suggests that individual differences may influence how effectively binaural beats entrain neural oscillations. Factors such as baseline cognitive performance, attentional state, and physiological responses to auditory stimulation may therefore influence how participants respond to binaural beat frequencies.

6. Conclusion

The objective of this experimental investigation was to determine whether different binaural beat frequencies influence reaction time in adolescents, with potential applications in educational or health settings. The results demonstrated an overall trend in which higher-frequency binaural beat stimulation was associated with faster reaction time, supporting the original prediction based on previous studies.

Analysis of the data showed that theta condition (6 Hz) produced the slowest mean reaction time, while the gamma condition (40 Hz) produced the fastest responses. In particular, a reduction of approximately 32.7 ms was observed between the theta and gamma conditions, indicating a clear negative relationship between binaural beat frequency and reaction-time performance.

However, although the overall trend supported the hypothesis, the results also displayed variability between individual participants. For example, Participant 7 demonstrated a consistent response pattern, showing a gradual decrease in reaction time as binaural beat frequency increased. This participant was noted to engage in regular athletic activity. Previous research suggests that adolescents who participate in athletic training often demonstrate faster baseline reaction times, improve sensory-motor coordination, and enhance neural efficiency. This may explain the consistent response pattern observed.

In contrast, Participant 3 demonstrated inconsistent reaction-time results, with the fastest response occurring under the theta condition (6 Hz), which contradicted the predicted trend. During testing, the participant reported feelings of heightened anxiety, and performance pressure, which may have influenced the results. Acute psychological stress activates the hypothalamic-pituitary-adrenal (HPA) axis, leading to increased cortisol secretion (Shields et al. 2016). Short-term increases in cortisol can temporarily enhance alertness and energy mobilization, potentially improving reaction-time performance. Therefore, the contradictory results may be explained by stress-related physiological responses rather than the binaural beat stimulus itself.

Despite these individual anomalies, the overall dataset ($n = 10$) continued to demonstrate a clear negative relationship between binaural beat frequency and mean reaction time. The presence of individual variation is likely reflective of natural differences in neural sensitivity, attentional state and physiological arousal.

In conclusion, the findings of this investigation suggest that binaural beat frequency may provide a non-invasive method for influencing adolescent reaction time performance, with higher-frequency stimulation generally producing faster responses. However, the magnitude of this effect can vary depending on individual sensitivity to auditory stimulation and physiological factors. Moreover, due to the lack of statistical significance ($p = 0.21$), the results should be interpreted with caution despite the observed trend. Future research involving larger sample sizes, longer exposure durations, and additional physiological measurements may provide further insight into the relationship between binaural beat stimulation and adolescent cognitive performance.

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Biography

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