

Auditory Stimulation and Attention: Effects of 40-Hz Frequency in Developmental Age

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Abstract: The study was conducted at the Explora Museum with the aim of investigating the effects of rhythmic sound stimulation on attentional and executive functions in children. The sample, consisting of 45 participants (ages 3–15; 25 females, 20 males), was divided into three experimental conditions: (1) neutral, characterized by the museum's ambient noise only; (2) museum composition, based on an audio track with a dominant frequency of approximately 196.8 Hz, located in the mid–low range of the sound spectrum, which served as a control condition to distinguish the general effect of music from the specific effect of rhythmic stimulation (40 Hz); and (3) low-frequency rhythmic stimulation (40 Hz), designed to enhance functional coherence and attentional control.

Assessment was carried out using the A1 subtest from the NEPSY-II battery (Brooks et al., 2009). Results showed significant differences between conditions ($H = 7.30$, $p = .026$): the group exposed to rhythmic stimulation achieved significantly higher scores than the neutral condition ($p < .05$). These findings suggest a facilitating effect of rhythmic sound stimulation and open new perspectives for neuroeducation and educational environmental design.

Keywords: Sound; Museum; Learning Environment



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1. Introduction

In recent decades, scientific interest in the relationship between environment and cognitive processes has grown significantly, highlighting the role of sensory stimuli in modulating attention, learning, and behavior. In particular, sound has progressively emerged as a key environmental variable, not only for its communicative function but also for its capacity to directly and indirectly influence individuals' cognitive and emotional processes (Conway et al., 2009). Attention, understood as a core function

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for the selection, organization, and processing of stimuli, appears to be especially sensitive to the qualitative and temporal characteristics of the sound environment.

During developmental stages, this sensitivity becomes even more pronounced, as attentional and executive systems are still maturing and are strongly influenced by the surrounding context. Educational and cultural environments, therefore, cannot be considered sensory-neutral, but rather should be examined as complex ecosystems in which visual, spatial, and auditory elements interact to shape cognitive experience. Within this framework, sound can assume a dual role: on the one hand, as a source of distraction or cognitive overload; on the other, as a design resource capable of supporting attentional processes and fostering optimal conditions for learning (Diamond, 2013).

At the same time, neuroscientific research has highlighted the role of brain oscillations in the regulation of cognitive functions, showing that specific frequency bands are associated with states of attention, alertness, and information integration. In particular, the 40 Hz frequency, within the gamma band, has attracted increasing interest due to its involvement in neuronal synchronization mechanisms and attentional processes (Chen et al., 2022). While these effects have been extensively investigated in adult populations, studies examining the impact of 40 Hz auditory stimulation during development, especially in ecologically valid contexts, remain limited.

In light of these considerations, the present article aims to explore the role of sound as a modulator of attentional processes within museum settings, with particular focus on the effects of 40 Hz auditory stimulation. The experimental research project was conducted at the Children's Museum of Rome – Explora, conceived as an educational and experiential space. The objective is to investigate whether and to what extent structured acoustic stimulation can influence attentional and executive performance in children and adolescents, thereby contributing to new perspectives for the design of educational environments informed by neuroscientific principles of learning.

2. Sound as a Modulator of Attentional Processes

Attention can be conceptualized as a dynamic and context-sensitive process through which cognitive resources are continuously allocated in response to both internal goals and external sensory demands. Rather than functioning as an isolated mental faculty, attentional regulation emerges from the interaction between neural control systems and the structure of the surrounding environment (Posner & Rothbart, 2007; Corbetta & Shulman, 2002). Within this framework, sound plays a distinctive role due to its temporal, pervasive, and often unavoidable nature. Unlike visual stimuli, which can be selectively excluded through gaze direction or eye closure, auditory information unfolds over time and continues to be processed even when it is not intentionally attended. This characteristic renders sound a particularly powerful modulator of attentional states, capable of sustaining vigilance, redirecting focus, or generating cognitive interference.

Comparative research on sensory modalities highlights important differences between auditory and visual attention that are central to understanding this modulatory role. While visual attention is predominantly optimized through spatial selection mechanisms, auditory attention is more strongly governed by temporal dynamics and anticipatory processes. Experimental evidence directly contrasting the two modalities indicates that spatial cues exert stronger effects on visual performance,

whereas temporal expectation more robustly enhances auditory processing (Wilsch et al., 2020). These behavioral differences are mirrored at the neurophysiological level: visual attention is closely associated with spatially specific modulations of alpha-band oscillations, whereas auditory attention relies more heavily on temporal alignment mechanisms supported by low-frequency oscillatory activity (Obleser & Kayser, 2019). From this perspective, attention to sound is intrinsically linked to timing, rhythm and prediction, rather than to spatial localization alone.

Consistent with this view, theoretical and empirical work on dynamic attending suggests that rhythmic and temporally structured auditory input can entrain attentional processes, aligning internal attentional oscillations with external events and thereby facilitating sustained focus (Large & Jones, 1999). Conversely, acoustically irregular or unpredictable environments disrupt this alignment, increasing attentional load and reducing processing efficiency. Sound thus functions not merely as background stimulation but as an active regulator of attentional load, capable of either stabilizing or fragmenting attentional engagement depending on its temporal organization and predictability.

These mechanisms are particularly salient during development, when attentional and executive systems are still undergoing maturation and remain highly sensitive to environmental modulation. A substantial body of developmental and educational research indicates that children are especially vulnerable to adverse acoustic conditions: elevated background noise and reverberation increase listening effort, impair selective attention, and negatively affect learning outcomes (Klatte, Bergström, & Lachmann, 2013; Nigg et al., 2024). Importantly, such effects are not merely perceptual but cognitive in nature, reflecting the additional executive resources required to maintain attention under acoustically demanding conditions.

At the same time, developmental plasticity also implies potential for positive modulation. Rather than conceptualizing sound exclusively as a disruptive factor, recent literature points to its capacity to support attentional development when appropriately structured. Sustained engagement with organized auditory experiences, most notably music training, has been consistently associated with improvements in executive functions closely linked to attention, particularly inhibitory control and selective focus. A recent meta-analysis integrating longitudinal and randomized studies confirms that music training in childhood yields reliable gains in inhibitory control, a core component of attentional regulation (Jamey et al., 2024). These findings suggest that temporally structured auditory input may function as a regulatory scaffold for attentional systems, rather than as a source of distraction.

Taken together, current evidence supports a shift away from dichotomous interpretations of sound as either “noise” or “support.” Instead, sound should be understood as a modifiable environmental variable whose attentional impact depends on its qualitative organization, temporal structure, and congruence with cognitive demands. This perspective provides a conceptual bridge between attentional theory and environmental experience, laying the groundwork for considering sound both as a defining element of lived spaces and as a potential resource for shaping attentional processes in educational and cultural contexts.

3. Sound in Educational and Cultural Environments

3.1. Sound as an Environmental Element

Sound is a carrier of information, in its primal function. From a biological perspective, it plays an important role in survival and orientation, allowing humans to perceive danger by locating sound sources and understanding their surroundings through the acoustic properties and characteristics of the spaces they inhabit. The human auditory system is a highly sophisticated one, adapted to detect variations in frequency, intensity and direction, and transforming these stimuli into meaningful information. By capturing these physical variations and decoding the information they carry, sound acts as a means of creating identity at multiple scales: from individual objects and human voices to entire spaces and environments. Every sound has a specific combination of frequencies and intensities that makes it unique, and in the same way, each environment is characterized by a combination of sounds that also makes it unique, defined by factors such as sound volume, quantity, domination, and individuality, among others. Therefore, there is an inextricable link between the vibrating object, the milieu in which the vibration spreads and the subject who listens. (Solomos, 2018). Sound is an intrinsic component of environmental identity, shaping how spaces are perceived and understood by those who inhabit them. As Schafer argues, from acoustics and psychoacoustics we learn about the physical properties of sound and the way sound is interpreted by the human brain, while from society we learn how humans behave with sounds and how sounds affect and change their behavior. (Schafer, 1977). This perspective highlights sound as both a physical and social phenomenon, or, as Solomos argues, as a network of relationships (Solomos, 2018). In consequence, sound as an environmental element can be understood as an evolving condition, continuously shaped by human activity while simultaneously reflecting and influencing human behavior and its evolution throughout history. Certain sound-related practices, such as singing during work or other communal activities, for example, have gradually been replaced over time by more mechanical or technologically produced sounds, creating new sonic environments that correspond to a contemporary way of living, evolving at the same pace as human activity and technology. As Korczynski describes it, there was a period in which music and work were mutually constituted to a significant degree, and then there is the period of industrialisation and mass production (...) characterised as involving a sharp divide between music and work. (Korczynski, 2003). Added to this, the sonic information of a certain environment has a direct impact on physical and psychological states, and the meaning attributed to sounds might affect our response to them. Sound is capable of generating powerful reactions in human beings which inform how they interact with and interpret their everyday environments. (Erfanian, Mitchel, Kang & Aletta, 2019), and different sound environments evoke distinct responses, influencing mood, emotions, attention and stress levels. For instance, quiet and pleasant sonic environments allow the listener full freedom and control over mind-states. In contrast, annoying sounds “force” one to be vigilant or to attend particular sources (Andringa & Lanser, 2013). Furthermore, sound functions as a means of shaping power dynamics, as Schafer notes, by allowing certain actors to occupy or dominate acoustic space (Schafer, 1977). Many aspects of sound influence and reflect both the environment and human behavior. This phenomenon is studied across multiple disciplines, addressing questions such as what sounds are, how they are perceived, what meanings they carry, and

what aesthetic value they possess. Together, these elements contribute to the identity of an environment, demonstrating that sound is not merely a background feature but an intrinsic factor in shaping how spaces are experienced and understood.

3.2 Noise, Silence and Structured Sound

Sound can be understood as the result of the dynamic interaction between three auditory components, noise, structured sound, and silence, which coexist and organize soundscapes within an environment. These categories are not fixed but relational and perceptually mediated, as human experience continuously negotiates their boundaries (Ihde, 2007). From silence to deafening noise, auditory perception operates within a continuous field shaped by attention and context. As Cage suggests, the position of a sound within this perceptual space depends on five determinants: frequency, amplitude, timbre, duration, and morphology (Cage, 1961). From a physical perspective, sound consists of pressure waves generated by vibrating objects, whose frequency is measured in hertz (Solomos, 2018). Human hearing typically ranges from approximately 20 Hz to 20,000 Hz, while infrasound and ultrasound remain beyond perceptual reach (Ihde, 2007). As Schafer notes, both absolute silence and total noise exist primarily as theoretical constructs, since neither can be fully perceived by the human ear (Schafer, 1977). Consequently, silence may be understood as a relative, anthropocentric concept, though it continues to function as a structural element of sound. Noise, sound, and silence can be examined across different disciplinary perspectives. Acoustics focuses on their physical properties, psychoacoustics on perceptual experience, and sound studies on cultural and social meanings. Noise is commonly defined as unwanted sound (International Organization for Standardization, 2016), characterized acoustically by random, non-periodic pressure variations (Kinsler et al., 2000), and psychoacoustically by negative listener judgment (Zwicker & Fastl, 1999). From a socio-cultural perspective, noise is a judgment rather than an intrinsic property of sound (Attali, 1977/1985).

Ambient noise refers to the accumulation of overlapping sounds within a given environment and is typically unstructured. The human brain, however, actively filters auditory input, allowing certain sounds to be ignored while others convey meaningful information. As Schafer observes, the same sound may be perceived as noise or signal depending on context (Schafer, 1970). When noise becomes informative, it transforms into structured sound, a carrier of meaning. Cage similarly argues that attentive listening enables the perception of structure even within environmental sounds (Cage, 1961). Structured sound refers to patterned auditory sequences that convey information, such as language or music (Patel, 2008). While music can be understood as noise organized according to a perceptible code (Cage, 1961), its meaning differs from linguistic semantics. Auditory perception is fundamentally synthetic: listeners perceive sounds as global gestalts rather than isolated elements, enabling recognition of melodies or linguistic meaning through structured sequences (Solomos, 2018). Sound structuring relies on multiple parameters, including rhythm, timbre, harmony, consonance, and dissonance. Silence plays a crucial role in this organization, introducing duration and temporal structure. As Attali argues, music exists in the space between noise and silence, shaped by social codification (Attali, 1977/1985). Cage further emphasizes that sound structures should be understood primarily in terms of duration

rather than frequency (Cage, 1961). Silence also functions structurally in language, organizing discourse in ways analogous to punctuation. Silence is perceptible only in relation to sound. As Schafer notes, silence preceding or following sound intensifies auditory experience, allowing sound to resonate in memory, thus, “silence sounds” (Schafer, 1977). This raises questions about the nature of silence itself. While some perspectives view silence as an inferred absence of sound, recent research suggests that silence is actively represented by the auditory system and functions as an object of perception (Goh, Phillips, & Firestone, 2023). Ultimately, noise, silence, and structured sound are defined by perception, context, and cognitive framing. Auditory input is decoded by the brain according to situational factors and attentional focus. As attention selectively prioritizes information across sensory modalities, sound perception emerges as an active, interpretive process rather than a passive reception of stimuli (Noyce, Kwasa, & Shinn-Cunningham, 2022).

3.3 Effects of Sound on Attentional Processes: 40 Hz

Sound represents a powerful modulator of cognitive processes and, in particular, of attention, understood as the ability to select relevant stimuli and inhibit irrelevant ones in relation to a specific goal. By its very nature, sound is a temporal and sequential stimulus, a characteristic that makes it especially relevant for the development of cognitive abilities related to time organization and the serial order of information. During developmental stages, these processes are still in the process of consolidation and appear particularly sensitive to environmental stimuli, including those of an auditory nature. From this perspective, auditory exposure, especially in the early phases of development, can play a structuring role in the construction of general cognitive skills, providing a form of auditory scaffolding that facilitates the processing and representation of complex temporal sequences.

According to the auditory scaffolding hypothesis, the auditory system contributes decisively to the development of sequencing abilities, supporting the learning and manipulation of serial-order information and effectively sustaining attentional and cognitive planning processes (Conway, Pisoni, & Kronenberger, 2009). Conversely, conditions of auditory deprivation during development may lead to difficulties in sequencing processes and attentional control, associated with phenomena of neural reorganization involving connections between the temporal and frontal areas of the brain, structures that are central to complex cognitive processing.

Within this theoretical framework, recent neuroscientific literature has devoted increasing attention to the effects of 40 Hz auditory stimulation, associated with the activation of gamma brain oscillations. Gamma waves, generally ranging from 30 to 80 Hz, are typically linked to states of heightened alertness, focused attention, and full consciousness; in particular, the 40 Hz frequency has been identified as especially relevant for attentional and mnemonic processes due to its role in neuronal synchronization and communication across distributed cortical networks (Jensen et al., 2007). Such synchronization facilitates the integration of sensory and cognitive information and is fundamental for efficient processing of environmental stimuli.

Recent studies have further shown that audiovisual stimulation calibrated at 40 Hz can significantly induce gamma oscillations, enhancing brain activity in areas involved in attention and memory through mechanisms of neural resonance that in-

crease oscillatory coherence and synaptic plasticity (Chen et al., 2022; Buzsáki & Wang, 2012). A particularly relevant line of research concerns the use of binaural beats (BB), auditory stimuli that, when presented separately to each ear, generate the perception of a beat at a specific frequency. Listening to 40 Hz BB has been associated with significant improvements in attentional performance, suggesting a direct effect on gamma oscillation activation (Englebregt et al., 2021), as well as positive effects on cognitive functions such as perception, motor skills, and memory (Gurtubay et al., 2004; Gross et al., 2005).

Finally, some evidence suggests that gamma stimulation at 40 Hz may promote forms of divergent thinking and cognitive flexibility, indicating a potential application of such stimuli in educational and cultural contexts oriented toward creative and attentional development (Negara et al., 2021). Overall, these findings support the hypothesis that the targeted use of 40 Hz sound frequencies may represent a promising strategy for modulating attentional processes during development, opening new applied perspectives in the field of auditory neurostimulation and the design of educational and experiential environments.

3.4 The museum as an educational and experiential space

In the contemporary context, museums are increasingly configured as educational and experiential spaces, capable of integrating cultural, cognitive, and emotional dimensions within an open and dynamic learning environment. Museum pedagogy, which has progressively developed between the twentieth and twenty-first centuries, has contributed to overcoming a conception of the museum understood exclusively as a place of conservation and passive enjoyment, instead promoting forms of active interaction and internalization of cultural and historical values (Milovanov et al., 2017). From this perspective, traditional educational practices, such as guided tours, now coexist with innovative and interactive approaches, fostering the visitor's direct involvement in the process of meaning-making.

The contemporary educational museum is grounded in an open cultural dialogue, in which the encounter with an artwork or exhibited object becomes an opportunity for interpretation, reflection, and participation. A central principle of this approach is the so-called *dialogue between epochs*, which enables the connection of the heritage of the past with the questions and experiences of the present through processes of cultural mediation and dialogic interpretation that actively involve the visitor (Aleksandrov, 2006, cited in Milovanov et al., 2017). In this sense, the museum is configured as a unique subject-space environment, in which the experiential dimension emerges from the interaction between the individual, the space, and the cultural object.

From a pedagogical standpoint, the educational value of the museum lies in its capacity to integrate cognitive, emotional, and sensory components, offering a formative experience that goes beyond the mere transmission of informational content. Museum pedagogy practices aim to stimulate creative potential, critical reflection, and active participation, particularly among children and young people, thus fostering meaningful and long-lasting learning processes (Pahomova, 2002; Burov, 2009, cited in Milovanov et al., 2017). Through interactive devices, workshops, thematic pathways, and innovative communication strategies, the museum becomes a

privileged space for informal and non-formal education, contributing to individuals' cultural, social, and personal development.

Within this framework, the museum represents not only a place for the preservation of collective memory, but also an active educational context, capable of responding to the transformations of contemporary society and fulfilling a central cultural and formative function, especially with regard to processes of growth and learning during development.

This perspective finds concrete application in institutions such as Explora, the Children's Museum of Rome, where the present research was conducted, which is conceived as a permanent informal learning environment oriented toward *learning by doing*. In this context, play, exploration, and experimentation become key tools for supporting cognitive and attentional development during childhood, confirming the role of the experiential museum as a strategic educational space for the observation and promotion of meaningful learning processes.

2. Materials and Methods

The Materials and Methods should be described with sufficient details to allow others to replicate and build on the published results. Please note that the publication of your manuscript implicates that you must make all materials, data, computer code, and protocols associated with the publication available to readers. Please disclose at the submission stage any restrictions on the availability of materials or information. New methods and protocols should be described in detail while well-established methods can be briefly described and appropriately cited.

Research manuscripts reporting large datasets that are deposited in a publicly available database should specify where the data have been deposited and provide the relevant accession numbers. If the accession numbers have not yet been obtained at the time of submission, please state that they will be provided during review. They must be provided prior to publication.

Interventionary studies involving animals or humans, and other studies that require ethical approval, must list the authority that provided approval and the corresponding ethical approval code.

4. Research Project

4.1. Research Hypothesis

Within the present research, it was hypothesized that rhythmic auditory stimulation at 40 Hz could promote an improvement in attentional and executive performance compared to control conditions.

4.2. Sample

The sample consisted of 45 children and adolescents aged between 3 and 15 years, all with typical development and no clinical reports or diagnoses of neurodevelopmental disorders. Participants were recruited on a voluntary basis among young museum visitors, with informed consent obtained from parents or legal guardians.

The participants came from diverse national and linguistic backgrounds, reflecting the multicultural composition of the museum context. For this reason, the A1 subtest of the NEPSY-II battery was selected (Brooks et al., 2009), as it assesses at-

tention and executive control abilities through non-verbal stimuli and visuoperceptual tasks, making it minimally sensitive to linguistic or cultural variables. This choice allowed the influence of extra-neurological factors related to language or schooling experience to be reduced to a minimum.

Participants were divided into three experimental groups of equal size ($n = 15$ each), balanced by gender (25 females and 20 males). Age and gender distribution was controlled to ensure homogeneous representation across experimental conditions. All children showed age-appropriate levels of cognitive and linguistic development, as verified through direct observation and information provided by parents.

Given the wide age range of the sample (3–15 years), it is important to note that participants were at different stages of executive function development. Although all showed typical development, inhibitory control, cognitive flexibility, and working memory are still rudimentary in preschool age and progressively consolidate through adolescence. This developmental heterogeneity suggests that auditory stimulation may have been integrated into the attentional task through different mechanisms depending on maturational stage, contributing to the observed interindividual variability.

Participants with sensory impairments (auditory or visual) or medical conditions that could interfere with auditory stimulus perception or cognitive performance were excluded. The tasks were conducted in an ecologically natural yet experimentally controlled setting within the museum space. The activity was presented to participants as an “attention game” in order to enhance motivation and reduce potential performance anxiety effects.

4.3. Materials and Methods

The experimental tasks were conducted in a museum environment, maintaining controlled conditions for all participants: the same room, the same time of day, constant lighting, and the same researchers. The independent variable manipulated was the auditory condition to which participants were exposed during test administration.

The study included three experimental conditions: (1) a neutral condition, characterized solely by the ambient noise of the museum; (2) a museum composition condition, based on an audio track with a dominant frequency of approximately 196.8 Hz, located in the mid–low range of the sound spectrum, which served as a control condition to distinguish the general effect of music from the specific effect of rhythmic stimulation at 40 Hz; and (3) low-frequency rhythmic stimulation at 40 Hz, aimed at enhancing functional coherence and attentional control.

To assess attentional and executive functions, the A1 subtest of the NEPSY-II battery was used (Brooks et al., 2009), which measures selective attention and cognitive control abilities. Raw scores were collected and subsequently converted into standardized scaled scores based on normative tables.

Each participant was tested individually, with a maximum session duration of 3 minutes. All sessions were recorded and stored in anonymized form.

The collected data were analyzed using descriptive statistics and inferential tests. After verifying the assumptions of normality (Shapiro–Wilk test) and homogeneity of variances (Levene’s test), the non-parametric Kruskal–Wallis test was applied, followed by Bonferroni-corrected post-hoc comparisons.

4.4. Data Analysis and Results

This section may be divided by subheadings. It should provide a concise and precise description of the experimental results, their interpretation, as well as the experimental conclusions that can be drawn.

Table 1. Descriptive statistics

Descriptive Statistics					
Groups	N	F	M	M	SD
A1 (neutral)	15	9	6	6,67	5,12
A1b (museum composition)	15	7	8	9,67	5,08
A1c (40 hZ)	15	9	6	12	3,82

This For each group, mean scaled scores and their corresponding standard deviations (SD) were calculated and are reported in Table 1. The A1 group (neutral condition) showed a mean score of 6.67 (SD = 5.12), the A1b group (museum composition) showed a mean of 9.67 (SD = 5.08), while the A1c group (40 Hz) obtained the highest mean score (12.00, SD = 3.82).

Overall, the data indicate a progressive increase in performance from the neutral group to the group exposed to 40 Hz stimulation, accompanied by a concurrent reduction in score variability. This pattern suggests a potential facilitating effect of auditory stimulation, particularly at 40 Hz, on the efficiency of executive functions as measured by the A1 subtest of the NEPSY-II battery.

Group differences were subsequently examined using inferential statistical tests to assess their statistical significance.

Table 2. Shapiro Wilk

Shapiro-Wilk			
Group	Statistic (W)	p-value	Result ($\alpha=0.05$)
A1 (neutral)	0,851	0,018	Not normal
A1b (museum composition)	0,926	0,24	normal
A1c (40 hZ)	0,933	0,305	normal

Table 3. Levene

Levene			
Test	Statistic	p-value	Esito ($\alpha=0.05$)
Levene	1,25	0,297	homogeneous variances

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Table 4. Kruskal-Wallis

Kruskal-Wallis			
Test	H	p-value	Result ($\alpha=0.05$)
Kruskal-Wallis	7,303	0,026	Significant differences

Given the violation of the normality assumption in one of the groups, a non-parametric Kruskal-Wallis test was employed, as it is suitable for comparing multiple independent groups when normal distribution cannot be assumed (Table 4). The test revealed a significant main effect of the experimental conditions on the scaled scores ($H = 7.30$, $p = .026$).

This result indicates that at least one group differed statistically significantly from the other two. From a descriptive standpoint, as previously observed, mean performance showed a progressive increase from the neutral group ($M = 6.67$) to the museum composition group ($M = 9.67$), and finally to the 40 Hz group ($M = 12.00$).

Overall, the outcome of the test suggests that auditory stimulation, and particularly stimulation at 40 Hz, may have exerted a facilitating effect on the executive and attentional functions measured by the A1 subtest of the NEPSY-II.

Table 5. Group Comparison

Group Comparison			
Comparison	p (Not correct)	p (Bonferroni)	Significant ($\alpha=0.05$)
A1 (neutral) vs A1b (museum composition)	0,1319	0,3958	–
A1 (neutral) vs A1c (40 Hz)	0,0078	0,0235	✓
A1b (museum composition) vs A1c (40 Hz)	0,25	0,7501	–

Following the significant result of the Kruskal-Wallis test ($p = .026$), post-hoc comparisons were conducted using Dunn's test with Bonferroni correction in order to identify which group pairs specifically contributed to the overall observed difference (Table 5).

The results revealed a significant difference between the neutral group (A1) and the 40 Hz group (A1c) ($p < .05$), indicating that participants exposed to 40 Hz

acoustic stimulation obtained significantly higher scaled scores than those who performed the task without specific auditory stimulation.

The difference between the neutral group (A1) and the museum composition group (A1b) did not reach statistical significance ($p > .05$), although a trend toward higher mean scores was observed in the group exposed to the sound composition. Similarly, the comparison between the A1b group (museum composition) and the A1c group (40 Hz) did not show statistically significant differences ($p > .05$).

Overall, the post-hoc comparisons confirm that exposure to a 40 Hz sound frequency is associated with better performance on the A1 subtest of the NEPSY-II compared to the neutral condition, suggesting a potential modulatory effect of temporally coherent acoustic stimulation on attentional and executive control processes.

5. Discussion

The results obtained from the A1 subtest of the NEPSY-II indicate that 40 Hz auditory stimulation is associated with a significant improvement in attentional and executive performance compared to the neutral condition. This effect appears to be specific to the 40 Hz frequency, as mere exposure to the museum sound composition did not produce statistically significant differences.

From a neurophysiological perspective, the 40 Hz frequency corresponds to the gamma oscillation band, which is implicated in sensory integration processes, sustained attention, and cortical synchronization (Buzsáki & Wang, 2012). Recent studies have shown that sensory stimulation at 40 Hz, whether visual, auditory, or tactile, can induce a phenomenon known as gamma entrainment, namely the synchronization of neuronal activity that promotes functional coherence across different cortical areas (Adaikkan et al., 2020; Iaccarino et al., 2016).

Numerous investigations have reported that such 40 Hz synchronization is associated with improvements in cognitive functions, particularly attention and working memory, as well as neuroprotective effects on cortical and hippocampal circuits (Martorell et al., 2019). For example, studies using gamma acoustic stimulation have demonstrated increased prefrontal neural responses and greater efficiency of auditory circuits (Han et al., 2023), further confirming the capacity of the 40 Hz frequency to specifically modulate attentional networks (Chen et al., 2022).

The findings of the present study fit within this framework, suggesting that exposure to structured acoustic stimulation based on physiologically relevant rhythmic frequencies (such as 40 Hz) may resonate with brain oscillations underlying attention, promoting a more balanced regulation of cognitive processes rather than generating noise or neuronal dissonance. In particular, the lower standard deviation observed in the 40 Hz group may reflect greater intraindividual performance stability, consistent with the hypothesis of a “functional synchronization” effect induced by gamma stimulation (Adaikkan et al., 2020; Iaccarino et al., 2016).

These results are consistent with the neuroscientific literature attributing a key role to gamma oscillations in perceptual binding and multisensory integration processes, and showing how 40 Hz stimulation can positively modulate brain connectivity and synaptic plasticity. The data suggest that the 40 Hz sound frequency represents a particularly effective stimulation condition for promoting cortical synchronization and, consequently, executive function efficiency.

However, given the wide age range of the sample, these findings must be interpreted in light of differences in neurocognitive developmental processes. It is well established that attentional systems and gamma oscillations undergo profound reorganization from early childhood through adolescence; therefore, 40 Hz stimulation may act through different mechanisms depending on maturational stage. In younger children, it may function as an external attentional scaffold, facilitating the regulation of control processes still under consolidation, whereas in older participants it may operate as a modulator of partially stabilized neural networks, enhancing their functional efficiency.

These findings open promising perspectives for neurodidactics and educational environmental design, in which the informed use of coherent auditory stimulation could serve as a positive modulator of attention and learning in museum or school contexts. Nevertheless, it is important to note that most existing research on the effectiveness of 40 Hz gamma stimulation has been conducted on adult or elderly populations, often in relation to cognitive decline or neurodegenerative conditions such as Alzheimer's disease (Iaccarino et al., 2016; Martorell et al., 2019; Adaikkan & Tsai, 2020).

6. Conclusions

When considering the impact of 40 Hz auditory stimulation on attentional processes, it is necessary to situate the results within a developmental and neurocognitive perspective. The literature on brain development highlights that gamma oscillations and attentional systems undergo progressive maturation throughout childhood and adolescence, reflecting the reorganization of cortical networks and the consolidation of executive functions (Uhlhaas et al., 2009; Uhlhaas & Singer, 2010). In younger children, fronto-parietal circuits responsible for attentional control are still developing, and attention is more strongly guided by bottom-up mechanisms that are sensitive to external sensory stimuli (Posner & Rothbart, 2007). At this stage, structured rhythmic stimulation may act as a sensory anchor, supporting attentional focus in complex environments.

By contrast, in older children and adolescents, the progressive strengthening of top-down control and executive functions allows for finer modulation of attention, making it plausible that 40 Hz stimulation may function as a regulatory factor for neural networks that are already partially consolidated (Diamond, 2013). To date, the scientific literature has not yet systematically explored the effects of gamma stimulation during development, nor its impact on key cognitive processes involved in maturation, such as attention, working memory, and executive control. Most of the available evidence derives from studies conducted on adult or clinical populations, in which gamma oscillations have been associated with mechanisms of cortical synchronization and functional integration across distinct brain areas (Fries, 2005; Thut, Schyns, & Gross, 2011).

The present study therefore represents an innovative contribution by applying the 40 Hz auditory stimulation paradigm to a sample of children and adolescents aged between 3 and 15 years. This choice allows the hypothesis that gamma synchronization mechanisms may be active and modifiable during development, extending current neuroscientific knowledge to a population that has so far been underexplored. The findings suggest that exposure to rhythmic auditory stimulation at 40 Hz may

positively modulate attentional and executive processes during developmental stages. These results are consistent with theoretical models attributing a central role to gamma oscillations in the temporal coordination of neural activity and in the efficiency of cognitive processing (Buzsáki & Draguhn, 2004; Fries, 2005), while nonetheless requiring a cautious interpretation grounded in developmental considerations.

However, the present study has several limitations. The relatively small sample size ($n = 45$) limits the generalizability of the findings, and the absence of direct neurophysiological measures (e.g., EEG or ERP) does not allow for direct confirmation of the induction of gamma oscillations. Moreover, the wide age range considered entails substantial maturational variability, which may have influenced the observed attentional performance. Future studies should therefore include larger and more homogeneous samples, integrate neurobiological indicators, and adopt longitudinal designs in order to clarify the underlying mechanisms and developmental trajectories associated with responsiveness to gamma stimulation.

Overall, despite the interpretative caution imposed by these methodological limitations, the findings open promising perspectives for neurodidactics and for the design of educational environments informed by neuroscientific principles of development. The idea that rhythmic sensory stimulation may support attention in educational and cultural contexts suggests new directions for research and intervention, oriented toward environmental design that takes into account the neurocognitive characteristics of different developmental stages.

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