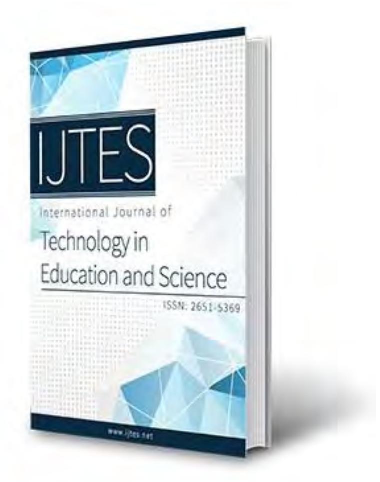

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Harmonies on the String: Exploring the Synergy of Music and STEM

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Harmonies on the String: Exploring the Synergy of Music and STEM

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Abstract

The process of perceiving music involves the transference of environmental physics in the air to anatomical and physiological interpretations of resonance in the body and psychological perceptions in the brain. These processes and musical interpretations are the basis of physical and cognitive science, neurophysiology, psychoacoustics, and cultural psychology. The intersection of interdisciplinary and transdisciplinary curricular offerings forms the basis of STEM (Science, Technology, Engineering, and Mathematics). In this study, the researcher explores the synergy of music in STEM for formulating and affording authentic STEAM programmatic offerings for learners. The blending of the art of music within STEM provides opportunities for teachers and students to address and connect content through creative, innovative approaches for deeper, meaningful learning. Threading the art of music within STEM affords discovery-learning opportunities that facilitate both critical thinking and social, emotional learning skills development in students. This study provides perspective in terms of developing curricular offerings for students that blend physical and cognitive science with the art of sound. The researcher provides authentic curricular exemplars regarding the synergy of music in STEM and concludes by offering recommendations for designing and implementing expressive curricular programmatic offerings for students from early childhood settings through higher education.

Introduction

Harmonies on the String

In a four-dimensional continuum, equations hum softly in the air
Atoms pulse with unseen energy and I hear the symphony of life

Beyond the confines of science where music and experimentation entwine
Imagination dances with improvisation and I sing the timbre of discovery

In the synergy of aesthetic science, the laws of physics and song resonate
Strings vibrate across guitar and cosmos and I feel the beat of nature's voice

The tempo of harmonies on the string are the ringing triads of divine creation
Arpeggios of inquiry and creativity echo and I strum the chords of knowledge….

Overture to Discovery: Exploring Music's Influence on STEM Education

Music is related to science through the study of cognitive science, neurophysiology, psychoacoustics, and cultural psychology, which provide an understanding of the cognitive and physiological aspects of musical perception and behavior (Cross, 1998). Understanding the threaded ties between music and science supports student understanding of scientific and social phenomena through the transdisciplinary and interdisciplinary construct of STEM (Science, Technology, Engineering, and Mathematics) education. The inclusion of art in STEM further results in the construct of STEAM for enhancing critical thinking and creativity for an authentic blending of art and science (Le Marec & Ribac, 2019). Studies have shown that participation in music, especially instrumental music, is important for supporting academic achievement, as music positively influences exam scores in content such as English, mathematics, and science and fosters competencies that support academic achievement (Guhn et al., 2020). A major goal of STEM education is to provide students with meaningful, blended curricula for student success. Therefore, the addition of music in STEM for STEAM is a philosophical construct that should be considered for fostering competencies that support critical-thinking and creative-thinking for student cognitive and emotive achievement and success not only in STEAM but also in the studies of the social sciences, languages, linguistics, culture, and psychology.

This research aims to thread what are typically perceived as diverging areas of study, *science and art*, into a converging tapestry of aesthetic experimentation for unified analyses and possibilities. The art of music is a science of art that personifies realized experimentation, improvisation and emotive connections for eliciting and furthering critical-thinking and creative thinking. Dignam (2022) stated, “Improvisation is experimentation of the spirit. Experimentation is improvisation of the mind. Free the mind and liberate the spirit” (p. 44). An overarching objective of this study is to present perspective in terms of the interrelatedness of music and STEM by providing historical backgrounds of each for intrinsically motivating and developing early childhood through higher education curricula that is innovative, creative, and includes opportunities for students of all settings to connect learning to their personal interests and lives. Creating a meaningful learning environment affords all learners with an atmosphere that supports cognitive, social, emotional, and mindful, nonphysical growth.

Mystic Rhythms: A Prelude to Teaching and Learning

Interdisciplinary teaching and learning includes multiple disciplines for providing diverse perspectives and methodologies for integrative thinking and problem solving (Bloomquist & Georges, 2022). An interdisciplinary construct fosters a deep understanding of complex issues by drawing on diverse methodologies and viewpoints and providing students with skills for addressing real-world challenges. Additionally, a transdisciplinary approach, as described by Liao (2016), eclipses disciplinary boundaries and interweaves collaborative and innovative approaches between disciplines. An interdisciplinary and transdisciplinary framework is inclusive and encourages students to explore content beyond traditional academic silos, preparing learners for the multifaceted demands of contemporary problem-solving.

Interdisciplinary approaches involve the integration of content knowledge and methods from different disciplines, while transdisciplinary approaches go beyond disciplinary boundaries to integrate knowledge and methods in a way that transcends traditional academic content areas, focusing on addressing complex real-world problems (Liao, 2016). Threading transdisciplinary and interdisciplinary constructs from multiple disciplines encourages collaboration, critical thinking, and creativity in preparing students for addressing practical problem-solving as a life skill (Clark & Button, 2011). As a consequence of stringing together insights from disparate disciplines, learners are equipped with comprehensive skill sets in furtherance of problem-solving for solution-finding. Interdisciplinary and transdisciplinary STEM for STEAM is a holistic methodological approach that broadens students' cognitive abilities as well as instills a sense of adaptability and resilience for social, emotional regulation essential for lifelong learning. Employing an interdisciplinary and transdisciplinary pedagogical platform equips STEM and STEAM teachers with a forum for presenting content across, between, and within curricula (see Figure 1).

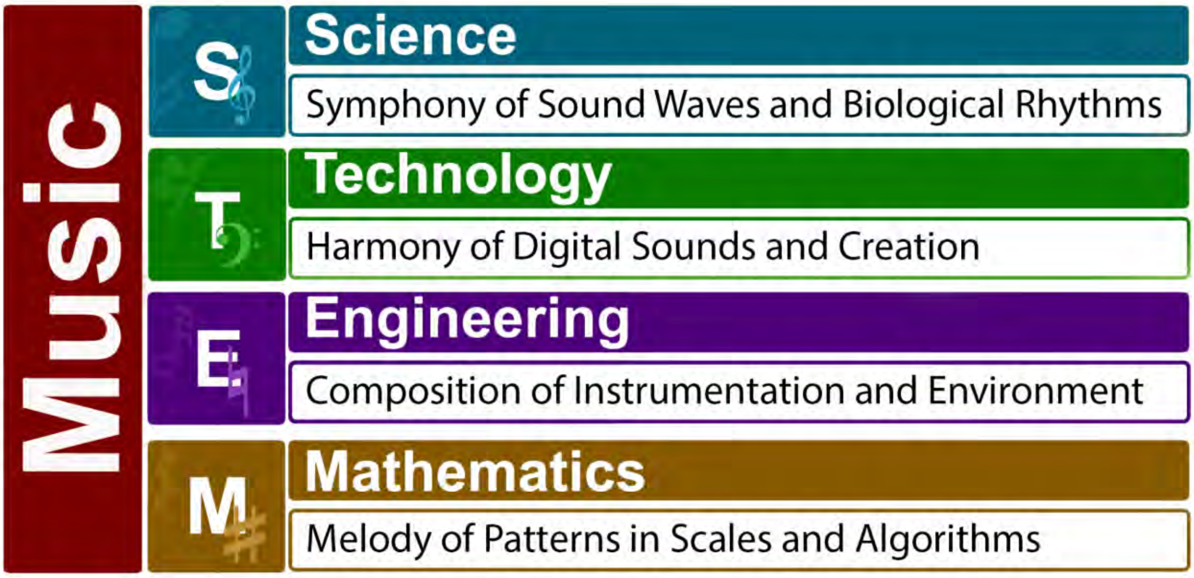

Figure 1. Music and STEM Across, Between, and Within Curricula

The Melody of Art in STEM to STEAM

Unifying Science, Technology, Engineering, and Mathematics as STEM is a philosophical transdisciplinary and interdisciplinary construct for better supporting student achievement. STEM employs transdisciplinary and interdisciplinary thinking for developing real-world solutions to 21st century dilemmas (Jia et al., 2021). The threading of art across, between, and within STEM sews design thinking and helps teachers by providing a structured approach to address classroom problems of practice, supporting the development of more creative and transdisciplinary and interdisciplinary teaching practices. The guiding of STEAM-based curricula by teachers amalgamates 21st century skills in learners for creativity and innovation (Henriksen, 2017). The transition from STEM to STEAM fosters the fusion of arts throughout STEM disciplines for interdisciplinary planning with a transdisciplinary framework among educators and enriched, creative learning for students (Liao, 2016). The addition of art also inspires students to engage in creative and imaginative design thinking for addressing authentic STEAM content within a transdisciplinary framework (Barth et al., 2023; Clark & Button, 2011). This study explores music and STEM through the lens of Dignam's 5 C's of STEAM Education; Constructing, Collaborating, Communicating, Critically Thinking, and Creatively Thinking (Dignam, 2021) and four types of learning (see Figure 2).

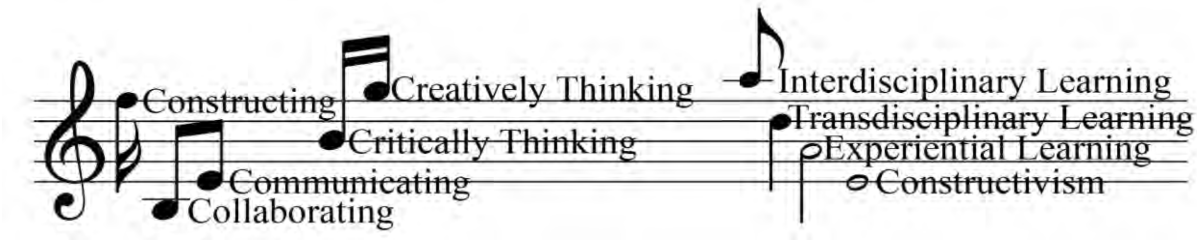

Figure 2. Dignam's 5 C's of STEAM Education and Four Types of Learning

Threading the Literature of Music and STEM

The Strings of Song and Science

Throughout this study, the researcher posits concrete exemplars of scientific and artistic inquiry alongside metaphoric contrasts relating to string theory. String theory represents a theoretical approach for unifying the descriptions of all fundamental forces and building blocks of the universe. (Ruehle, 2020). String theory also attempts to unify general relativity and quantum mechanics for universal, theoretical understanding. The researcher employs the theoretical construct of string theory as creatively analogous to music and STEM in a variety of ways. String theory proposes that the most fundamental building blocks of the universe are vibrating strings (Ibanez & Uranga, 2012).

Theoretical one-dimensional strings can vibrate at different frequencies, giving rise to the various particles and phenomena observed in nature. Strings are smaller than even subatomic particles such as atoms, electrons, and quarks. The concept of vibrational patterns creating different outcomes resonates strongly with the essence of music, where distinct musical notes and harmonies arise from different vibrational frequencies (Isola, 2021; Metzger, 2020). Employing parallels between the vibrational nature of the strings proposed in string theory and the harmonics produced by vibrating strings in musical instruments such as the guitar enables educators to introduce students to complex scientific ideas in an engaging and conceptual manner. Interdisciplinary and transdisciplinary approaches for exploring the synergy of music and STEM fosters a deeper comprehension of both the workings of the universe and the principles underlying musical creation.

Moreover, the mathematics that describes the vibrations and oscillation patterns of strings within string theory draws upon concepts that are also fundamental for music theory and composition (Erbin, 2024; Ibanez & Uranga, 2012). The mathematical relationships governing the intervals, chords, and scales of music can be expounded upon through STEM principles such as ratios, geometric progressions, and group theory, which share parallels in the mathematical frameworks of vibrating strings in string theory (Aasim, 2018; Alam & Mohanty, 2023). Exploring mathematical connections within and across music and science enables educators to foster a deep appreciation for the inherent beauty and interconnectedness that permeates STEM disciplines in students. The interdisciplinary exploration of mathematical harmonies resonates in physics and oscillates in the forms of musical compositions within the universe. Furthermore, when educators thread music and mathematics, they are empowered to develop interdisciplinary and transdisciplinary STEAM curricula for nurturing and inspiring students to investigate relationships across and between various subjects and engage in innovative, creative thinking (Henriksen & Mehta, 2023). The philosophical threading, weaving, and interlacing of string theory for music in STEM for STEAM is the philosophical construct the researcher posits throughout this study for entwining the vibrational energy of science, aesthetics, and emotive connections for learning.

Moreover, string theory acts as a unifying thread that connects technological innovation with interdisciplinary and transdisciplinary curricula and research. String theory has catalyzed the development of novel mathematical techniques, computational algorithms, and experimental methodologies that find applications beyond fundamental physics. These applications span diverse fields that include materials science, quantum computing, and data analysis (Schuhmacher et al., 2023; Sood & Chauhan, 2024). In addition, the creative and analytical skills that are developed and nurtured through music education can enrich STEM disciplines by cultivating innovative approaches to problem-solving, fostering interdisciplinary collaboration, and driving scientific discovery. Sewing the threads of music and STEM creates opportunities for composing harmonies of artistic expression and melodies of cognitive development for resonant teaching and learning.

The Resonance of Mechanics

The mechanics of physics and sound are abiotic factors that are interpreted by biotic structures within the human body. The conversion of the non-living elements of sound and how sounds are perceived as music rather than noise is illustrative of STEM and STEAM, as myriad processes are required to transform seemingly inert, environmental properties into cognitive, emotive, sensate interpretations. Understanding how physical sound in the environment translates into anatomical, physiological, and psychological experiences of perceiving and cognizing that sound involves an elaborative process. Sound originates as waves traveling through the air from the surrounding environment. When sound waves reach the ears, a series of transformations occur, converting physical waves into neural signals that the brain can interpret (Kramer & Brown, 2021; Moller, 2000). Sound waves first interact with the outer ear, funneling through the ear canal to vibrate the eardrum (Green, 2021; Yost, 2021). Vibrations pass through the small bones of the middle ear into the inner ear's cochlea, where it causes movement of tiny hair cells. The motion of hair cells triggers electrical signals that travel along the auditory nerve to the brain (Moller, 2000; Yost, 2021). This transformation from physical sound waves to neural impulses allows the brain to process and make sense of auditory input.

The human auditory system is designed to detect and comprehend varying characteristics of sound waves, enabling the perception of a diverse range of frequencies and amplitudes (Kramer & Brown, 2021). Physiologically, the process of interpreting physical sound into information the brain can process involves converting the mechanical energy of sound waves into electrical signals. The cochlea, a spiral-shaped cavity in the inner ear, plays a critical role in this transduction, with different regions responding to different frequencies of sound (Moller, 2000; Yost, 2021). The anatomical and physiological interpretation of sound waves within the body results in the ability to perceive music.

The translation of physical sound from the environment into anatomical and physiological sensations is a dynamic process that ultimately results in the perception of music (Kramer & Brown, 2021). The brain's comprehension of sound is shaped by past experiences, cultural context, and cognitive processes between sensory input and higher-order cognitive functioning (Athanasopoulos et al., 2021; Vuust et al., 2022; Welch et al., 2020). The complex relationship among environmental physics, anatomy, and physiology reveals the mechanisms underlying music perception and how these perceptions can be leveraged in educational settings, such as STEAM programmatic offerings, to enrich learning and stimulate innovative creativity.

The Timbre of Perception

Music perception in the brain involves processing diverse components of musical stimulus across different regions, starting with the primary auditory cortex handling raw acoustic signals, which is subsequently distributed to association areas and other cortical regions (Warren, 1999). Increased brain activity is triggered by the temporal regularity of sound stimuli, leading to significant activation in the primary auditory cortices and distinct patterns noted in the anterior-posterior brain regions (Griffiths et al., 1998). Various aspects of musical processing, including rhythm, pitch intervals, melody, and timbre, are managed by separate neural networks within the brain (Reybrouck et al., 2020; Warren, 1999).

Sounds observed as music influence cognitive and emotive responses in listeners and further influence psychological, physical, and emotional well-being. Music impacts attentiveness and stimulates brain activity, enhances cognitive processes, and reduces distractions, ultimately improving focus and cognitive performance (Das et al., 2020). The brain combines sensory, cognitive, and emotional systems with reinforcement circuits to generate musical pleasure by interacting with regions responsible for auditory perception, advanced temporal sequencing, and emotional processing (Salimpoor et al., 2015). The complex interactions of brain systems are multifaceted, and the nature of music's influence on human cognition and emotion is a multidimensional phenomenon of the threading of STEM and psychology.

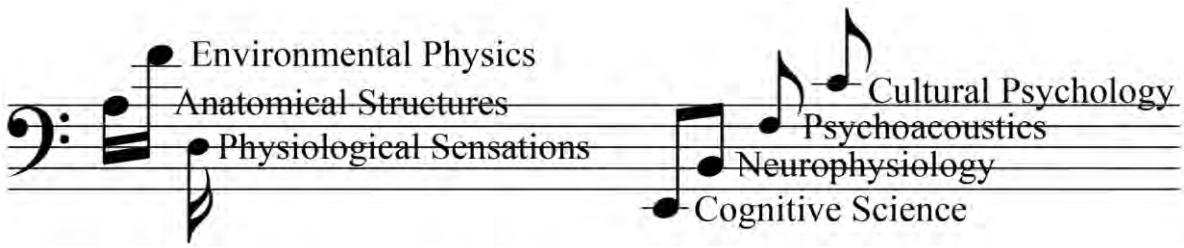

Figure 3. The Translation of Environmental Physics into Music

The neurological foundations of music perception reveal insights into how the brain processes and responds to auditory stimuli. Neural networks dedicated to rhythm, pitch, harmony, melody, and timbre processing demonstrate the specialized functions of different brain regions in music perception (Reybrouck et al., 2020; Salimpoor et al., 2015; Warren, 1999). Understanding these neural mechanisms provides insight regarding music cognition and principles of brain function and organization. Insights derived from exploring music perception in the brain threaded within and throughout STEM holds significant practical implications across and between disciplines, including cognitive science, neurophysiology, psychoacoustics, and cultural psychology. The synergy of music and STEM produces opportunities for creating innovative methodologies for constructing and employing curricula that addresses cognitive functions and emotional wellness through a music-centered approach (see Figure 3).

Psychological and Cognitive Science

The study of how individuals interpret and make sense of the world around them includes the domains of psychological perceptions and cognitive science. Both fields explore mental processes, including perception, memory, reasoning, and problem-solving (Athanasopoulos, 2021; McAdams, 1987). In terms of music, psychological perceptions refer to the subjective experiences and interpretations that individuals possess when exposed to auditory stimuli such as music. Stimulated experiences include emotional responses, aesthetic judgments, and developing preferences for certain musical genres or compositions (Athanasopoulos, 2021).

Cognitive science, on the other hand, aims to understand the underlying cognitive mechanisms involved in perception and thought processes, such as how sensory information is processed, stored, and retrieved in the brain (Cross & Deliège, 1993; Pearce & Rohrmeier, 2012). Research in cognitive science sheds light on how individuals extract meaningful patterns from musical stimuli, how musical structures are encoded and remembered, and how attentional processes influence the perception of music, providing insights into the impact of music on awareness and appreciation (Harwood, 1976; Särkämö, 2013; Vuust et al., 2022; Welch et al., 2020).

Neurophysiology

Neurophysiology examines how the body's nervous system and associative neurons communicate and process stimuli anatomically and with respect to behavior. In a study by Di Liberto et al. (2021) the researchers utilized neurophysiology for investigating how the brain reacts and continuously predicts sensory signals, vital for understanding sensory perception during silence and while listening to classical music in relation to sensory perception. When listeners heard Bach, their brains reacted by comparing what they heard with what they expected to hear, showing different patterns for silence and imagined music compared to actually listening, demonstrating a clear connection between how individuals anticipate music and how the brain reacts to it (Di Liberto et al., 2021).

In a study on brain activation patterns during music listening by Chan & Han (2022), the researchers examined how passive music listening in healthy individuals activated multiple cortical, subcortical, and cerebellar regions of the brain and music listening could potentially modulate disordered functional brain networks in neurological disorders. The neurophysiology of music demonstrated the effects of music preferences on brain activation patterns among patients with neurological disorders such as Autism Spectrum Disorder (ASD) and Alzheimer's Disease (AD) for promoting the development of music as a personalized medicine (Chan & Han, 2022). The neurophysiology of music has the potential to enhance cognitive functions in both healthy individuals and those with neurological disorders by advancing personalized medicine strategies for physical and emotional well-being.

Psychoacoustics

Psychoacoustics is a branch of psychophysics that examines physiological responses as a result of perceiving sound and provides insight into how sensory experiences, such as music, can influence cognitive processes. In a study by Barbaroux et al. (2021) on musician and non-musician sound perceptions, speech, and cognitive processing, the researchers identified that musicians demonstrated an enhanced skill in categorizing speech sounds compared to non-musicians, suggesting a higher level of precision in processing auditory information. Enhanced categorical perception, as observed in musicians, might benefit STEM education by refining students' abilities to categorize and comprehend intricate STEM concepts (Barbaroux et al., 2021; Kachlicka et al., 2019; Leeniva & Upala, 2015). Refined auditory processing skills may enhance student comprehension and interpretation of scientific data, particularly in domains where sound plays a critical role, bolstering students' cognitive capabilities and problem-solving skills in science and technology disciplines. Enhancing students' auditory processing skills can result in better understanding and the interpretation of scientific data and has the potential to enhance students' cognitive abilities and problem-solving skills across STEM fields.

Cultural psychology

Biology and culture are interrelated and influential in terms of innate and learned musical abilities. For example, infants possess the ability to discriminate pitch, and by the time most children become school-aged, they possess an aptitude for recognizing and differentiating diatonic tones within the seven notes of major or minor scales (Justus & Bharucha, 2002). Cultural exposure to music impacts brain development and tonal proclivities particular to specific cultures. Children's musical development is influenced by cultural factors and enculturation, which shape their exposure to different musical styles and practices, resulting in a sense of musicology, identity, and emotional connectedness (Hodges, 2019; Justus & Bharucha, 2002). Culture influences how individuals relate to music, affecting their feelings of inclusion, personal beliefs, and ties to particular musical customs or activities (Jacoby et al., 2020). The threaded nature of music and psychology provides insight into how music is perceived as a result of experiences and the influence of experiences on cognition (Deutsch, 2019). A comprehensive understanding of the psychological processes of music processing can provide insight for developing teaching methodologies for integrating music into STEM for affording students an inclusive environment for STEAM inquiry.

Acoustic Landscapes: The Dynamics of Sound in STEM Education

The utilization of existing neural networks aids in the perception of sound as music, and the act of listening to music stimulates new neural networks that not only discern musical notes, but also results in auditory stimuli of sensory, cognitive, and emotional systems in the body. The means by which the physical environment is perceived through senses and translated into physiological experiences is further elucidated by fields such as psychology, cognitive science, neurophysiology, psychoacoustics, and cultural psychology. Scientific, psychological, and cultural foundations provide a comprehensive understanding of how individuals perceive and interact with music within the broader context of their biological, cognitive, and sociocultural backgrounds. Furthermore, the translation of environmental physics is a tapestry of sound waves that create phenomena such as frequency, wavelengths, harmonics, amplitude, and timbre that result in sensory, cognitive, and emotional responses, giving way to musical notes, chords, scales, melodies, harmony, and rhythm comprehension (see Figure 4).

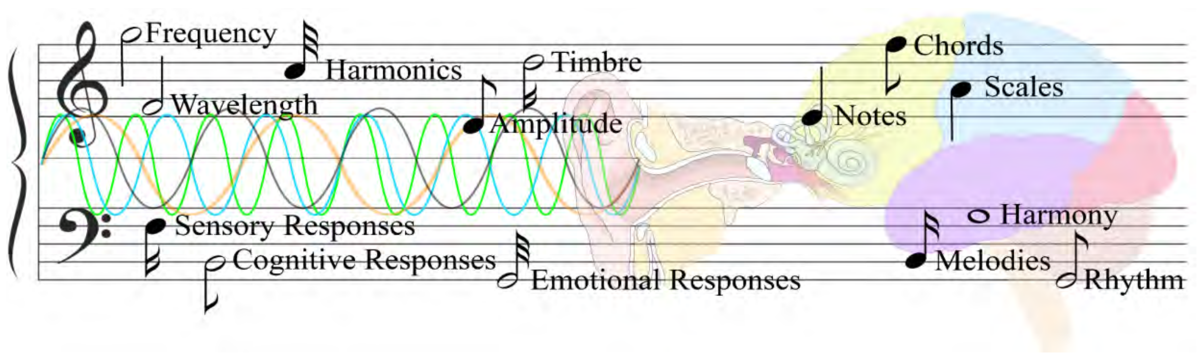

Figure 4. The Mechanics of Musical Perception

Frequency

The frequencies of musical notes are governed by mathematical expressions rooted in the fundamental physical properties of sound waves. In Western musical traditions, the most widely employed system for determining note frequencies is equal temperament tuning. An equal temperament tuning system divides an octave into 12 equal semi-tonal intervals by applying a geometric progression to the fundamental frequency. (Jones, 2022; McAdams, 2019). The dividing of 12 notes is an authentic exemplar of the synergy of music and STEM. Equal temperament tuning is based on what is termed a musical octave, which begins with a single note and a corresponding note that is a doubling of the first note's frequency (Hardegree, 2023; Jones, 2022). The frequent distance between the two notes is uniformly divided by twelve, which creates a 12-note, equally tempered chromatic scale, with both mechanical physics and musical note properties.

Frequency is measured in hertz (Hz), which is a standard measurement of one oscillating event per second. As a result of determining and creating a 12-note, equally tempered chromatic scale, each note in the scale can be measured in Hz, which further results in each note possessing a reference frequency measured in events per second (Gunther & Gunther, 2019; Jones, 2022). Each of the 12 notes are musically referred to as half-steps or semitones, with each semitone also being measured in one-hundredths for fine musical instrument tuning (Gunther & Gunther, 2019). The frequency of a note (f) is calculated using the formula $f = f_0 \times 2^{(n/12)}$. For example, f_0 is the frequency of a reference note, such as A4 (the fourth A note in a string of octaves), which is the unit measure 440 Hz and n is the number of half steps (semitones) away from the reference note. The equal temperament frequency formula enables a consistent division of the octave interval across all musical keys, resulting in equal frequency ratios between adjacent semitone steps. Systematic uniformity greatly influences modulations across diverse tonal keys within the Western musical standard (Jones, 2022).

Wavelength

When sound moves through the air, it moves as a wave, with sound waves conceptually behaving somewhat similar to waves of water moving up and down and bouncing or reflecting backwards or forwards (Gunther & Gunther, 2019). A wavelength **(λ)** is inversely proportional to frequency and is characterized by the physical distance between successive peaks (or troughs) of a sound wave. The relationship between frequency (f), wavelength (λ), and the speed of sound (v) is expressed as $v = f \times \lambda$.

The reciprocal relationship between wavelength and frequency dictates that as the wavelength of a wave decreases, its corresponding frequency increases inversely and proportionally (Gunther & Gunther, 2019). Consequently, when a wave has high wavelength, it inversely possesses low frequency. An increase in frequency (shorter wavelength) results in high pitch of sound. A decrease in frequency (longer wavelength) results in low pitch of sound. The inverse relationship between wavelength and frequency is proportional and constant (Jones, 2022). The inversely proportional properties of wavelength and frequency/pitch exemplifies the art and science of physics and music (see Figure 5).

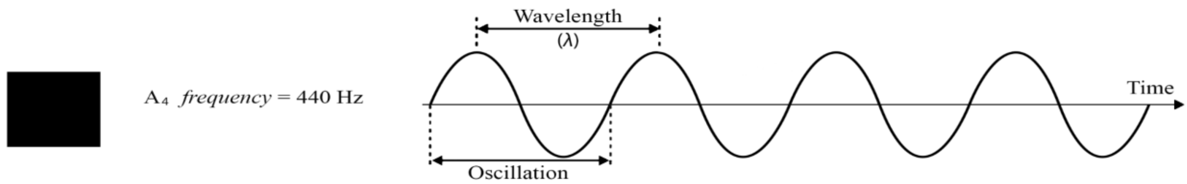

Figure 5. Properties of Frequency and Wavelength

Harmonics

Musical tones are complex waveforms that, in addition to the fundamental frequency that determines the perceived pitch, contain harmonic overtones with frequencies that are integer multiples of the fundamental (McAdams, 2019). The additional frequencies present occur at whole-number multiples of the fundamental frequency. The frequency of the nth harmonic (f_n) can be calculated as $f_n = n \times f_1$ where n is the harmonic number.

Western music almost universally uses "A" 440 Hz as the reference note for tuning, which allows standardized 12-note, equally tempered chromatic scales above and below A4 440 Hz. Using A4 440 Hz as a reference point, harmonic frequencies can be derived for each fundamental frequency or musical note to calculate harmonics using the formula $f_n = n \times f_1$. For example, the first, fundamental harmonic frequency (f_1) for the musical note A4 440 Hz equals A4 440 Hz. Using the harmonic formula, the second harmonic number (n) for the fundamental frequency and musical note A4 440 Hz, can be solved by $f_2 = 2 \times 440$, with $f_2 = 880$ *Hz.* Each harmonic number for thereafter would result in $f_3 = 1760$ *Hz,* $f_4 = 3520$ *Hz, and so on.*

Harmonic formulas offer a mathematical framework for expressing the relationships between the frequencies of musical notes, their physical characteristics, and the neurological mechanisms of pitch perception in music. The physical principles governing harmonics provide a fundamental understanding of various facets of music theory, composition, and acoustics. Fundamental knowledge allows musicians and researchers in STEM fields to analyze and manipulate sound waves, facilitating the creation of diverse and harmonious musical experiences that influence the inherent properties of acoustic vibrations. Mathematics, physics, and musical artistry utilize harmonic formulas to express the sounds perceived as music and the cognitive processes that gives rise to the emotive experiences by music (Jones, 2022; McAdams, 2019; Yan & Tu, 2022). The science of harmonics is often referred to as overtones in music and are important for musicians to aesthetically manipulate when performing music.

Amplitude

In the context of music, the amplitude of a sound wave corresponds to the magnitude or intensity of the acoustic vibrations. Amplitude quantifies the relative strength of the propagating sound waves, which is subjectively experienced as the loudness or volume of the auditory stimulus (McAdams, 2019). Amplitude correlates with the wave's height, representing the variation in air pressure from the peak to the trough of the wave. Mathematically, amplitude (A) can be represented as $A = P_{\text{peak}} - P_{\text{trough}}$. Alternatively, amplitude can be described in relation to the maximum displacement from equilibrium ($D_{\max}$) of the medium through which waves propagate. The equation for the amplitude of simple harmonic motion can be used to establish a connection between displacement and maximum pressure, $A = 2 \text{ x } D_{\max}$. Within harmonic motion, $D_{\max}$ denotes the farthest distance of air particles from their resting state due to the influence of the sound wave. Defining sound wave amplitude requires using sine and cosine functions as sinusoidal functions for determining the maximum displacement of sound waves in the air (the vibrational pressure of sound waves from the equilibrium position).

The sinusoidal function of a sound wave is $y(t) = A \sin(2\pi ft + \phi)$. The sinusoidal function for amplitude provides peak and trough values for the soundwave with $y(t)$ representing the displacement (y) at time (t); A for amplitude; f for the frequency; and ϕ for the phase angle. For the following example, phase angle will be set to 0, or a standard position, meaning the phase will neither be positive ($\phi>0$) nor negative ($\phi<0$). Additionally, and for the purposes of this study, phase angle shift or offsets will be simplified as 0 to illustrate a waveform that has not shifted (delayed or advanced) relative to time.

In maintaining previous examples using A4 440 Hz as the fundamental note, if A4 is f=440 Hz and equals two units of sound wave displacement (A = 2 units for positive or negative displacement) with a phase angle $\phi = 0$, the peak value occurs when $\sin(2\pi ft+\phi) = 1$ and trough value occurs when $\sin(2\pi ft+\phi) = -1$. The peak value would be $P_{peak} = A\times 1 = A = 2$ and the trough value would be $P_{trough} = A\times(-1) = -A = -2$. Amplitude can therefore be calculated using $A = P_{\text{peak}} - P_{\text{trough}}$, resulting in 2 – (-2) = 2=2 = 4 (four units of displacement, indicating the magnitude of the sound increased).

The characteristics of sinusoidal and threshold formulas illustrate how amplitude relates to the physical properties of sound waves and provide a quantitative measure of the loudness or intensity of sound for auditory sound perception resulting in response and sensation (McAdams, 2019). In music, amplitude provides an understanding regarding dynamics influencing the perceived volume and emotional impact of a musical passage (Yan & Tu, 2022). Understanding the mathematical representation of amplitude is grade level and age-appropriate-specific and can help students appreciate the relationship between physical phenomena and the auditory sensations they experience when listening to music as a result of translating mechanical science into music, art, and perception

(Yan & Tu, 2022). Exploring the concept of amplitude in the context of music and STEM education can provide opportunities for interdisciplinary and transdisciplinary learning, connecting principles of physics, acoustics, and psychoacoustics for auditory science with musical theory and performance.

Timbre

Timbre is related to psychoacoustics and known as tone color or tone quality. Timbre is the perceived sound quality of a musical note, sound or tone. In many ways, timbre is a synergistic translation of mechanical physics and emotional, cognitive perceptions, as the interpretation of tone color and tone quality are properties of physics as well as anatomy, physiology, and psychology (Gunther & Gunther, 2019; Yan & Tu, 2022). Timbre distinguishes different types of sound production and instrumentation. Timbre is a multifaceted perceptual quality that serves as a distinguishing feature among various musical sounds, even when their pitch and loudness remain identical (Jones, 2022). Although no single formula can precisely quantify timbre, its neural perceptions are shaped by various factors, including harmonics, envelopes, spectral content, and transient characteristics (McAdams, 2019).

Harmonics and overtones contribute to timbre and give rise to characteristic tone quality dependent on the distribution and strength of harmonics. Overtones create a color or resonance of sound while harmonics provide multiple fundamentals, adding to the perception of the sound (Yan & Tu, 2022). The temporal structure of a sound wave, encompassing its attack, sustain, decay, and release, influences the shaping of timbre through its envelope. These characteristics, which denote changes in amplitude and determine whether the sound is perceived as sharp or smooth, percussive or sustained, significantly impact timbral qualities (McAdams, 2019; Yan & Tu, 2022). Perceived envelopes contribute to the neurons in the brain distinguishing the resonating and vibrating strings of a guitar from those of a mandolin from just hearing the sound. The spectral content and distribution of energy across the frequency spectrum of a sound wave influences its timbre (Yan & Tu, 2022). Various musical instruments and vocal timbres exhibit distinct spectral profiles, marked by peaks and troughs in frequency response, contributing to their individuality (McAdams, 2019). Furthermore, transient characteristics, such as the brief bursts of energy at the onset of a sound, such as the initial attack of a plucked or strummed note on a guitar, play a significant role in shaping timbre. Transient features influence the perceived sharpness, brightness, or dullness of a sound (McAdams, 2019; Yan & Tu, 2022).

Harmonics, envelopes, spectral content, and transient characteristics enrich and shape the timbre of sound through mechanical physics translated anatomically, physiologically, and psychologically as music (Jones, 2022). Harmonics, as integer multiples of the fundamental frequency, contribute to the value and complexity of a sound's spectral content, while overtones, though not multiples, also add to the complexities of characteristics. Envelopes describe how the sound evolves over time, influencing its attack, sustain, decay, and release, which in turn affects its transient characteristics. Together, these elements create the unique sonic identity of musical instruments and sound sources, enriching the timbre by adding layers of complexity, character, and expressive possibilities (Jones, 2022; Margulis et al., 2023; Yan & Tu, 2022). Understanding physical, anatomical, physiological, and psychological phenomena are essential for creating interdisciplinary and transdisciplinary STEAM teaching and learning.

Strings of Discovery: The Verse, Chorus and Bridge of Music and STEM

Musical Notes

Sounds that are perceived as music consist of individual pitches and are named using the letters A through G, with sharps ($^{\#}$) or flats ($^{\flat}$) added to indicate alterations in pitch and for memorizing in staffs in sheet music, thereby translating aural qualities of sound into visual, textual, and numeric literacies. Western music contains 12 pitches, or notes, and are named A, $A^{\#}/B^{\flat}$, B, C, $C^{\#}/D^{\flat}$, D, $D^{\#}/E^{\flat}$, E, F, $F^{\#}/G^{\flat}$, G, and $G^{\#}/A^{\flat}$ (Bras-Amorós, 2020). Notes can be played individually, in series, as a combination of two notes as a dyad, or as three notes forming a triad, which further results in chords and can include additional notes in chording beyond the triad (Jones, 2022). Each musical note also correlates to its environmental physical properties, consisting of a distinct wavelength and frequency measured as Hz. As a result of the physical properties of notes and their vibrational measures of Hz, when notes are combined, they tend to sound agreeable (consonant) or tense/disagreeable (dissonant) as a consequence of their interacting sound waves. The vibrations between combined notes are what cause notes, dyads, and chords to either sound as though they are "in key" or "out of key" (Gunther & Gunther, 2019). Perceptions of consonance, discord, harmony, melody, and the rhythm of music itself elicit psychological and physiological emotional responses, vibrating and oscillating like strings in the minds of each listener, resulting in emotive reactions.

Intervals

The distance between each note or pitch is referred to as an interval. Intervals are commonly referred to as perfect, major, or minor (Bras-Amorós, 2020; Hardegree, 2023). When a single note is played, it contains a fundamental note and its harmonic series. Harmonics are natural multiples of the fundamental note and sound agreeable, or consonant. The most agreeable or consonant notes are either unisons of the same note (a perfect prime) or an octave of the fundamental, called a perfect octave. A perfect octave is the same note at either lower or higher pitches, such as A3 220 Hz and A4 440 Hz, or A4 440 Hz and A5 880 Hz. The wavelengths of each octave align and are consonant. Similarly, the wavelengths of notes or pitch can be arranged as ratios, with a perfect prime being 1:1 and an octave being 2:1 (Hardegree, 2023). Other perfect intervals include the perfect fifth (3:2) and the perfect fourth (4:3). A simultaneously played root note, or tonic, of A4 440 Hz with a perfect fourth D5 587.33 Hz illustrates the 4:3 relationship between waves (see Figure 6).

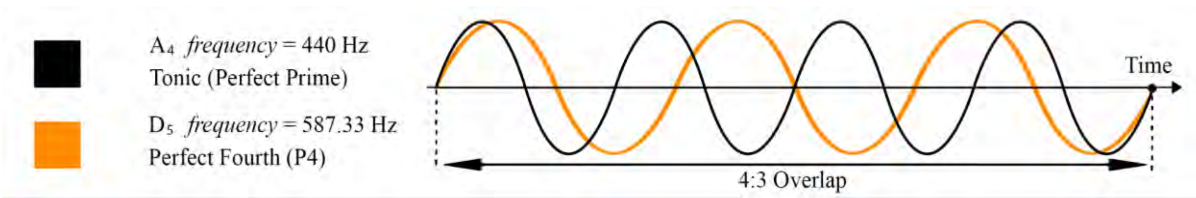

Figure 6. A4 440 Hz and a Perfect Fourth D5 587.33 Hz

The perfect fifth is harmonically stable and has a pleasing sound to the ear, making it an essential building block in harmony and chord progressions (Bras-Amorós, 2020; Melo, 2023). The perfect fifth is a fundamental interval that naturally occurs in the harmonic series, which is a series of frequencies that are integer multiples of a fundamental frequency. When a string or column of air vibrates, it produces a fundamental frequency and overtones that are multiples of the fundamental frequency. The first overtone in the harmonic series is a perfect fifth above the fundamental frequency. The natural occurrence of the perfect fifth contributes to its sense of stability and consonance (Clader, 2018). A simultaneously played root note, or tonic, of A4 440 Hz with a perfect fifth E5 659.25 Hz illustrates the 3:2 relationship between waves (Figure 7). Intervals such as major and minor thirds, sixths, and sevenths are considered imperfect intervals due to their varying degrees of consonance and dissonance (Hardegree, 2023; Jones, 2022; Melo, 2023). Imperfect intervals contribute to the rich harmonic palette of music but may possess different qualities compared to the perfect intervals.

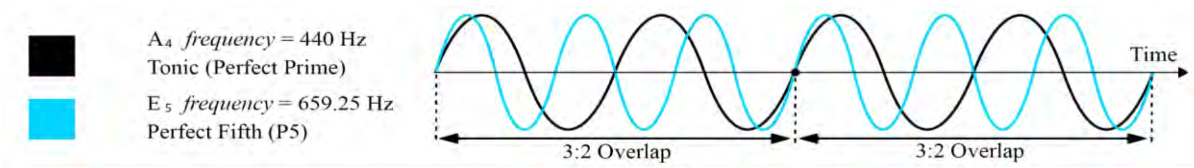

Figure 7. A4 440 Hz and a Perfect Fifth E5 659.25 Hz

Semitones and Frequency Ratios

The sequential order of the 12 notes that comprise Western musical pitches begins with the tonic or fundamental and ends with the perfect octave of the fundamental, with each step in between separated by a semitone. The relationship between music and STEM are observable as frequency ratios between the tonic and each semitone, expressed as whole numbers. The auditory system tends to find simple frequency ratios that produce octaves, perfect fifths, perfect fourths, major thirds, etc. the most agreeable, while complex frequency ratios that occur in minor seconds, minor sevenths, or augmented fourths (tritones) spanning three whole tones are perceived as disagreeable. When harmonic intervals are perceived as agreeable, their consonance communicates a sense of resolution. Harmonic intervals that are perceived as disagreeable tend to communicate discord and a sense of tension. The vibrational energy of frequencies are harmonies on the string that span the spectrum of musicology, STEM, the social sciences, language, linguistics, culture, and psychology. The oscillating relationship between a fundamental note and the 12 notes that comprise Western musical pitches are expressed as musical semitones with corresponding whole number ratios (see Table 1).

The interval between the tonic and each semitone consists of distinct frequency ratios, and the vibrational energy between the frequencies of the tonic and each semitone's sound wave will result in subsequent musical pitches that sound either consonant or dissident. For example, the frequency of the Minor Second is about $\frac{16}{15}$ times the frequency of the tonic, which sounds dissonant and results in perceived tension. Additionally, the Augmented Fourth possesses a frequency that is approximately $\frac{45}{32}$ times the frequency of the tonic, resulting in the most disagreeable, dissonant incidence rate. Contrariwise, the frequency of the Perfect Fourth is about $\frac{4}{3}$ times the frequency of the tonic, which sounds consonant. Moreover, the frequency of the Perfect Fifth is about $\frac{3}{2}$ times the frequency of the tonic, which sounds the most resolute aside from a perfect prime or octave.

Table 1. Semitones and Frequency Ratios

Semitone	**Whole Number Relationships**
Tonic (Perfect Prime)	Frequency ratio of 1:1
Minor Second (m2)	Frequency ratio of 16:15
Major Second (M2)	Frequency ratio of 9:8
Minor Third (m3)	Frequency ratio of 6:5
Major Third (M3)	Frequency ratio of 5:4
Perfect Fourth (P4)	Frequency ratio of 4:3
Augmented Fourth (or Tritone) (A4)	Frequency ratio of 45:32
Perfect Fifth (P5)	Frequency ratio of 3:2
Minor Sixth (m6)	Frequency ratio of 8:5
Major Sixth (M6)	Frequency ratio of 5:3
Minor Seventh (m7)	Frequency ratio of 16:9
Major Seventh (M7)	Frequency ratio of 15:8
Octave (Perfect Octave)	Frequency ratio of 2:1

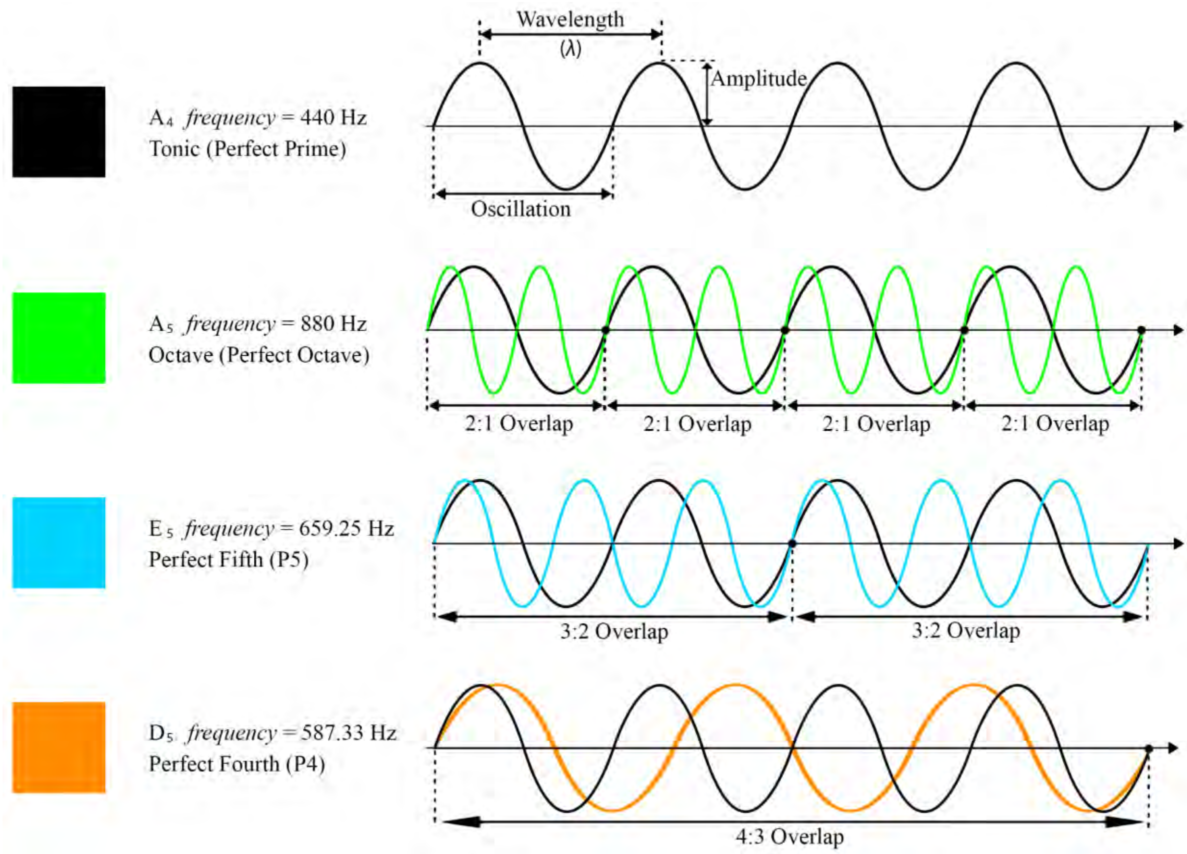

Figure 8. Comparative Analysis of Frequency, Wavelength, and Ratios

Visually, we can examine and conduct a comparative analysis of a tonic (perfect prime), an octave (perfect octave), a perfect fifth (P5,) and a perfect fourth (P4) to observe the ratios of three exemplar semitones and how the corresponding wavelengths overlap in relation to the tonic or fundamental note. Playing A4 440 Hz (black) simultaneously with its octave A5 880 Hz (green) results in a 2:1 overlap cycle. In addition, playing A4 440 Hz (black) simultaneously with a perfect fifth E5 659.25 Hz (blue) results in a 3:2 overlap cycle. Moreover, playing A4 440 Hz (black) simultaneously with a perfect fourth D5 587.33 Hz (orange) results in a 4:3 overlap cycle. The physics, biology, and psychology of simultaneously played musical notes is influenced by the overlapping cycles of frequency ratios. Semitones such as minor seconds and augmented fourths possess cycles that are interpreted as displeasing or dissonant as a result of the high ratios and disruptive overlapping of simultaneous pitches (see Figure 8).

Scales

The frequency ratios described provide a musical, STEM-related, physiological and psychological translation of the relationship between the frequency of each degree and the frequency of the tonic. The art and science of music includes a series of structured notes that form the basis of scales in composition. Scales are based on the frequencies and prescribed ordered pitch of notes and form a basis for harmonious and melodic patterns that align with the pitch, or key, of musical chords in composition. The vibrational energy of scalar frequencies and their anatomical, physiological, and psychological consonant or dissonant interpretations are influenced by either their simple or complex frequency ratios. In Western music, scales follow a prescribed pattern of semitone or whole tone steps between 12 possible notes that are fundamental and unique for each individual scale.

Western music typically consists of diatonic scales, which are a pattern of seven series of notes, followed by an eighth note, the octave. Diatonic scales are often referred to as seven degrees of the 12-note chromatic scale, with the eighth note being the octave of the fundamental or tonic, first-degree note. Arranging scales with seven unique pitches followed by the repetition of the initial pitch at a higher or lower octave enables composers and musicians to construct readily identifiable patterns for scalar tonality and harmonic progressions. Diatonic scales are typically termed major or minor based on their semitone patterns while the chromatic scale consists of all notes available within the octave. Composers and musicians often include additional pitch options of notes beyond diatonic scales for chromatic embellishments, alterations, and modulation. The 12 chromatic notes, when combined with the diatonic scale's pitches, introduce diversity, tension, and a spectrum of colors to musical compositions, enhancing the harmonic richness and expanding expressive potential of song.

Refraining Traditions: Threading the History of Musical Progressions

The Pythagorean Scale and Just Intonation

Musical instruments and the notes they produce must follow procedures for tuning in an effort to ensure musical compositions sound concordant as opposed to discordant. The tuning of notes results in concordant or discordant dyads, triads, chords, and scales. The Pythagorean scale and Just Intonation are scales of ancient origins with formulas for tuning. The Pythagorean scale originated sometime around 600 B.C., with Just Intonation beginning thousands of years earlier and may be as old as music itself (Clader, 2018; Nyhoff et al., 2023). The Pythagorean scale begins with the fundamental and tuning the fifth (multiplying the frequency by $\frac{3}{2}$) that results in the octave aligning precisely with the third harmonic within the harmonic sequence (Bras-Amorós, 2020; Melo, 2023). The next sequence involves tuning yet another fifth by multiplying the second frequency by $\frac{3}{2}$, thereby piling compounded fifth after fifth. While the Pythagorean system maintains pure fifths, it often results in dissonances in other intervals (Nyhoff et al., 2023; Pitkänen, 2016). The Pythagorean scale served as a cornerstone for highlighting the mathematical interconnections among musical pitches, which provided a framework for early Greek scholars and mathematicians to delve into the intricacies of sound harmony. Pythagorean philosophy highly influenced Western philosophical studies, including the domain of music (Nyhoff et al., 2023; Pitkänen, 2016). Dozens of centuries later, these philosophical and mathematical constructs would come to influence ideas related to string theory for unifying relativity and quantum mechanics.

Just Intonation is an ancient tuning system that uses simple whole number frequency ratios derived from the harmonic series for determining interval ratios. Interval ratios are either half-step intervals (adjacent semitones) or whole-step intervals (two semitone intervals). A half step interval refers to the distance between two adjacent notes in a chromatic scale (Nyhoff et al., 2023). The distance between half steps is $\frac{256}{243}$ times the frequency (*f*) of the preceding half step. For example, beginning with A4 440 Hz and then moving up a half step results in $A^{\#}_4/B^{b}_4$ and can be calculated as: $f_{A\#} = f_A \times \frac{256}{243}$. In Just Intonation, the distance between whole step intervals is $\frac{9}{8}$ times the frequency (*f*) of the preceding whole step (two semitones). Utilizing Just Intonation with A4 440 Hz and then moving up a full step results in B_4 and can be calculated as: $f_B = f_A \times \frac{9}{8}$. While Just Intonation derives intervals that are tuned to pure, whole number ratios with harmonic relationships, Just Intonation possesses limitations in terms of dissonant frequency modulations requiring constant pitch corrections (Melo, 2023; Nicholson & Sabat, 2019).

Equal Temperament Scale

Western music is defined by the use of equal temperament tuning for seven degree, major and minor scales of the 12-note chromatic scale. Equal temperament tuning divides the octave into 12 equal parts, with each of the 12 semitone intervals (aside from the octave) possessing the same measured ratios. The ratios of each semitone are equal intervals, allowing music to be played in 12 different keys by instruments that do not require retuning. Equal temperament is based on the twelfth root of two, which is approximately 1.059463. The formula $r = \sqrt[12]{2} = 2^{1/12}$ allows for multiplication of the 12 notes of the chromatic scale by $(\sqrt[12]{2})^n$ for deriving tuning frequencies and wavelengths for each chromatic interval (Clader, 2018; Gunther & Gunther, 2019; Melo, 2023). The fundamental of a given note can be used for calculating corresponding equal temperament frequency and wavelength (see Table 2).

Western music equal temperament tuning was influenced by the Pythagorean philosophy of concordance and standardizes the transposition of music. However, the frequency ratios between notes in equal temperament tuning deviate slightly from the precise whole-number ratios that occur in tuning systems based on pure harmonics, such as Just Intonation, and compromises tuning purity. While equal spacing occurs between intervals, none of the intervals are perfectly in tune with their pure harmonic counterparts, resulting in dyads, triads, and chords not being perfectly in tune with themselves at different positions. As a result, instruments are never perfectly in tune with themselves. Nonetheless, equal temperament allows modulation across keys, sanctioning music to be transposed with standardized tuning and affords harmonic instrument accessibility for performance and composition.

Table 2. Equal Temperament Calculations

Note	Calculation	Frequency	Wavelength
A_4	440 Hz	440.00 Hz	78.41
$A^{\#}_4/B^{b}_4$	$440 \times \sqrt[12]{2}$	466.16 Hz	74.01
B_4	$440 \times (\sqrt[12]{2})^2$	493.88 Hz	69.85
C_5	$440 \times (\sqrt[12]{2})^3$	523.25 Hz	65.93
$C^{\#}_5/D^{b}_5$	$440 \times (\sqrt[12]{2})^4$	554.37 Hz	62.23
D_5	$440 \times (\sqrt[12]{2})^5$	587.33 Hz	58.74
$D^{\#}_5/E^{b}_5$	$440 \times (\sqrt[12]{2})^6$	622.25 Hz	55.44
E_5	$440 \times (\sqrt[12]{2})^7$	659.25 Hz	52.33
F_5	$440 \times (\sqrt[12]{2})^8$	698.46 Hz	49.39
$F^{\#}_5/G^{b}_5$	$440 \times (\sqrt[12]{2})^9$	739.99 Hz	46.62
G_5	$440 \times (\sqrt[12]{2})^{10}$	783.99 Hz	44.01
$G^{\#}_5/A^{b}_5$	$440 \times (\sqrt[12]{2})^{11}$	830.61 Hz	41.54
A_5	$440 \times (\sqrt[12]{2})^{12}$	880.00 Hz	39.20

Fission and Fusion: The Interplay of Elements

Harmony

Harmony is a combination of musical notes that are played simultaneously to form chords and chord progressions. Chords form from three or more intervals of notes played together, with the movement between chords forming a sequence called a chord progression (Chan et al., 2019). The chords within musical progressions form relational movements that add emotion to music, resulting in tension, resolution, and space for complimentary musical passages to interplay based on the structure of chords and progressions. In addition, and as a result of utilizing the 12 notes of a chromatic scale from equal temperament tuning, 12 different keys are derived, with each key possessing a specific type of associative notes for creating and organizing harmony and chords. The perception of harmonious or inharmonious (discordant) passages in music are reliant on which of the 12 musical keys the composition is written and played in and determined by physical properties between the frequencies of the notes played together. The art of notes and science of frequency in musical harmony is anatomically, physiologically, psychologically, and culturally perceived as either harmonious or discordant based on the physics of intervals between frequencies.

Melody

Melody refers to a series of musical notes that constitute the primary theme of a composition, leading to its easy recognition and retention by listeners (Horton et al., 2020; Yeh et al., 2021). Melodies are musical contours that create a flow in terms of pitch progressions, chords, and lines, with notes moving and telling an aural story through musical lines and chord progressions. Melody lines also contribute to perceptual tensions and resolutions in music and compliment harmony, chord progressions as psychoacoustics (Chan et al., 2019). Melodies form the basis of pitch sequences that move much like oscillating waves upon vibrating strings with repetitive phrasing and motifs that create memorable melodic lines. In addition, infant-aged children possess the ability to draw out and identify melodies from musical stimuli, distinguishing familiar melodies from unfamiliar lines as early as two months old, and by five to six months, infants can recall melodies even when altered in pitch (Cirelli et al., 2018). The ability of infants to perceive and remember melodies highlights early learner responsiveness to music and opportunities for parents and early childhood educators to employ music as a form of cognitive and social, emotional atmospheric learning.

Rhythm

According to Grunow (2021), rhythm is an aural and kinesthetic property of music that is both perceived and felt by listeners. Aural properties of music refer to how rhythm is heard and understood, while kinesthetic properties relate to how rhythm is physically experienced and expressed through movement. Musical rhythm includes beat-based structures with equal time intervals for precise predictions and synchronized movement, as well as nonbeat-based structures with systematic timing, accent, and grouping not tied to temporal periodicity (Ozernov-Palchik & Patel, 2018). While rhythm provides patterns for sequencing harmony and melody, the rhythmic properties of music also possess educational learning implications for early childhood, kindergarten, and primary education settings. Repetitive, rhythmic and melodic singing to infants facilitates caregiver-child bonding and promotes a sense of relaxation and nurturing between early childhood teachers and infants as well as bonding and nurturing between parents and infants (Provasi et al., 2021). Rhythmic interactions with caregivers in early childhood settings help infants socially by fostering bonding, communication, and emotional connections through shared musical experiences, promoting prosocial behavior and social preferences towards familiar rhythms and synchronous movements (Cirelli et al., 2018). In addition, rhythmic synchronization between a caregiver's singing and physical touch during skin-to-skin contact with an infant offers the infant participatory, multisensory stimulation and promotes synchronized interaction between a mother and child (Provasi et al., 2021). Beat-based processing in music for kindergarten-aged children and early primary school learners can influence early reading skills while the neural processing of beat-based musical rhythms in infants influences phonological abilities that serve as foundational supports for subsequent grade levels (Ozernov-Palchik & Patel, 2018).

Method

Portraits of Inquiry: Methodological Exploration in Music-Infused STEM

Lawrence-Lightfoot & Davis (1997) developed portraiture methodology for investigating the collective, lived experiences of individuals through phenomenology, narration, ethnography, and case study. Portraiture integrates empirical inquiry with descriptive, aesthetic elements for entwining art and science and offers a nuanced perspective for enriching research practice and comprehension alike. The researcher employed a portraiture methodological approach centered on phenomenology and narration for creating rich, synergistic music-in-STEM descriptive analyses. Additionally, the construct employed provides autoethnographic accounts of phenomena, allowing the researcher to employ narration and perspective for aesthetic, scientific descriptive analyses within personal contexts (Gaztambide-Fernández et al., 2011; Golsteijn & Wright, 2013; Hackmann, 2002; Quigley et al., 2015).

Results and Discussion

Symphonic Findings: Unveiling the Impact of Music on STEM

Music learning in the context of STEM for STEAM can have a positive role in children's development, including cognitive abilities, social skills, and self-esteem (Ilari, 2020). The inclusion of music in STEM for STEAM correlates with and has been shown to improve student assessment success in mathematics, science, and English, which are key components of STEM education (Guhn et al., 2020). In a study conducted by Cross (1998), three different views related to the relationship between music and science were identified and consist of the cognitivist position, which focuses on scientific explanations of abstract representations of musical events, the physicalist view, which attempts to comprehend music in the same way as physics, and the societal view, which considers societal factors that influence scientific inquiry. In concert, the positive impacts of music and STEM are oscillations that resonate through every aspect of education, fostering creativity, critical thinking, and holistic development.

Threading and interweaving music in STEM *and* STEM in music enhances student cognition through inquiry, collaboration, and identifying patterns of STEM within music *and* music within STEM. Providing opportunities for students to engage in synergistic music and STEM *and* STEM in music learning also promotes critical-thinking, creative thinking, social skills development, and emotionally connects learners to the content for holistic learning. Moreover, STEAM leverages a multidisciplinary approach that engages and capitalizes on student emotions, and impacts both cognitive and emotional aspects of teaching and learning, as emotions influence memory, attention, and cognitive abilities (Steele & Ashworth, 2018).

STEAM fosters social, emotional learning through interdisciplinary and transdisciplinary student engagement, promoting resilience, teamwork, problem-solving, and communication skills, while nurturing a collaborative environment for building social capital for prosocial skills development (Liao et al, 2016; Rikoon et al., 2018). Interlacing music in STEM further enhances cognitive-emotive processes by cultivating social capital, fostering collaboration, communication, and teamwork skills essential for academic and professional success. Moreover, braiding music into STEM education nurtures creativity, accommodates diverse learning styles, and increases student engagement (Allina, 2018; Puccia et al., 2021). Embracing music's influence on STEM enables educators to enhance academic proficiency and foster essential life skills to prepare students for success in subsequent grade levels, and eventually, the workforce.

Melodic Insights: Exploring Music's Influence on STEM Education

Music enriches STEM education by moving beyond passive memorization and facilitating a deep understanding of scientific concepts by engaging students emotionally through interests and affording a variety of approaches to addressing science content (Crowther et al., 2016). Threading music and STEM allows students to connect with content on a personal level and enhances students' understanding and retention of scientific concepts through a more inclusive and engaging learning experience. In a study by Rahmat et al. (2023), students' critical thinking skills were examined through interlacing music and STEM by exploring musical instrument building and utilizing Phyphox app technology for conducting sound wave experiments. The research assessed how music, science, and technology influenced student critical-thinking skills development as well as the exploration of culture related to musical instrument construction. As a result of blending music, STEM, and culture, students developed critical thinking skills related to interpretation, analysis, evaluation, inference, through practical engagement with instruments and the use of meaningful sound wave technology on mobile devices (Rahmat et al., 2023). Providing learners with multiple pathways for exploring content in a student-centered environment enhances the retention of academic material and personalizes meaning (Awad, 2023; Crowther et al., 2016). Engaging in contextual learning, experiential learning, collaborative learning, Information and Computer Technologies (ICT)-based learning, and project-based learning can greatly boost students' knowledge, learning abilities, and self-confidence (Awad, 2023). The interweaving of music within each STEM discipline is summarized in Table 3.

Table 3. Synergy of Music within Each STEM Discipline

STEM Discipline	Interweaving Music
Science	**Acoustics:** Sound waves and frequencies to neural impulses **Physics:** Vibrations and oscillation patterns, String theory (General relativity and quantum mechanics) **Biology:** Anatomy of the ear (small bones of the middle ear, cochlea, hair cells, electrical signals, auditory nerve) **Neurophysiology:** Anatomical, physiological, and psychological experiences, temporal sequencing, neural stimuli, processing, and emotional processing **Cognitive Science, Psychoacoustics, and Cultural Psychology:** Cultural context, cognitive processes, sensory input, discernment **Chemistry:** Materials of instrument construction and sound production
Technology	**Music Production Software**: Digital tools for composing and editing **Electronic Instruments**: Synthesizers, drum machines, and MIDI **Apps and Coding**: Generative music
Engineering	**Instrument Design:** Blueprinting, constructing **Instrument Building:** Designing, creating, and innovating **Sound Engineering:** Recording techniques past and present **Tonewoods and Metallurgy:** Qualities of instrument fabrication **Amplification:** Sound systems and speakers for air movement

STEM Discipline	Interweaving Music
Mathematics	**Rhythm and Timing**: Patterns/beats, time signatures, temporal periodicity **Scales and Tuning:** Frequency ratios, Pythagorean Scale, Just Intonation **Relationships:** Intervals, chords, scales, computational algorithms, threshold formulas, harmony and calculations, sinusoidal functions **Materials Science:** Quantum computing, and data analysis

Early Childhood Education

Introducing STEAM in early childhood creates an environment that enriches learning with heightened motivation, engagement, creativity, self-assurance, and inclusive experiences tailored to early childhood emotional and social growth (Voicu et al., 2022). In early childhood education, musical play enables children to engage in exploration, experimentation, self-expression, role adoption, and storytelling through music. Immersive musical-STEM experiences not only enhance collaborative and interactive skills but also positively impacts children's language development and interaction abilities, contributing to improved early childhood development and communication proficiency (Pitt, 2020). Moreover, in early childhood education settings, music enriches students' social and emotional development, language and literacy skills, cognitive and intellectual growth, and fosters self-regulation, motor development, and language and literacy skills through engaging activities (Kirby et al., 2023). The integration of music and STEM principles in early childhood settings provides a holistic learning environment for very young learners to thrive cognitively, socially, and emotionally.

Kindergarten

The ability of children to perceive rhythm and musical movements are observable beginning in early childhood education and kindergarten. Children are naturally endowed with inherent rhythmic and musical abilities that require repeated exposure through kinesthetic activities for further developing musical and rhythmic abilities (Laure & Habe, 2024). Music and STEM helps kindergarten children enhance their logical-mathematical abilities, including counting and musical notation, by participating in activities that include rhythmic exercises, playing instruments, and singing (Incognito et al., 2022). Incorporating music into STEM at the kindergarten level can foster interdisciplinary learning, as it encourages children to explore connections between music and mathematical concepts, such as patterns and sequences. Involving kindergarten students in music education programs can also have a positive impact on cognitive flexibility and potentially improve executive functioning and prosocial behaviors in children (Ilari et al., 2021). Engaging kindergartners in musical STEM activities helps children develop artistic expression by threading creativity and analytical thinking.

Primary Education

Music in STEM for STEAM enhances the overall development of primary school children by supporting cognitive growth, social, emotional skills development, the advancement of visual, textual, numeric and digital literacies, critical thinking, inquiry, and problem-solving abilities. Additionally, STEAM supports the development of social skills such as self-image, self-esteem, self-efficacy, resilience, empathy, teamwork, and communications in learners (Voicu et al., 2022). Integrating music education into digital-based STEAM increases students' creativity, improves learning, and positively impacts students' cognitive, affective, and social development (Özer & Demirbatir, 2023). Interdisciplinary and transdisciplinary art in STEM in primary education fosters the development of student’s critical thinking, creative thinking, and innovation by engaging learners in activities centered on creativity, design, and practical problem-solving (Uştu et al., 2022). In primary school settings, engaging students in instrument design through blueprinting, constructing, and performing music using the instrument created affords learners with practical learning that promotes creativity, problem-solving, and collaborative teamwork (Cheng et al., 2022). Moreover, exposing primary school students to music as part of their STEAM education inspires exploration and discovery, as students learn to apply STEM principles in designing, creating, and innovating for meaningful learning.

Secondary Education

Participation in secondary education STEAM programs that entwine music and STEM provides students with opportunities to engage in both hands-on and digitally-based curricula for examining the applications of music in STEM *and* STEM in music. Programmatic offerings such as sound engineering support learning across the spectrum of technology, mathematics, and music within STEAM (Guhn et al., 2020). A high school sound recording program helps students make meaningful connections between school music education and students’ personal musical lives by providing hands-on opportunities to create, produce, and distribute original and creative work (Clauhs et al., 2019). When students engage in technological, mathematical, and physics-based music activities, they are enabled to explore a variety of topics ranging from the frequency of sound waves to calculating the qualities of pitch, musical notes, and musical instrument engineering and construction. In secondary STEM settings, diversifying classrooms into specialized groups that align with students' distinct musical interests also allows for more tailored instruction and activities that tap into each learner's passion and motivation to drive engagement (Gage et al., 2020). Creating opportunities for personalized learning in multipurpose classroom settings at the secondary level also promotes ownership of the learning and a motivation to engage in relevant exploration of STEM-music content. Furthermore, secondary education programs that integrate music into STEM provide students with a holistic approach to learning, fostering not only technical skills for sound engineering and musical instrument design and construction, but also critical thinking, creative thinking, collaboration, and communications for meaningful learning.

Higher Education

In higher education settings, Higher Music Education (HME) stands out for emphasizing creativity, cultural entrepreneurship, and social responsibility through artistic citizenship for the betterment of society (Gaunt et al., 2021). Integrating music with STEM through science provides opportunities for creative and expressive learning that enhances students’ vocabulary acquisition through rhythm, melody, lyrics, and musical compositions (Hughes et al., 2022). Incorporating music into STEM at the higher education level can enhance lectures, assignments, and projects, leading to increased engagement and effectiveness in learning for college students. Intertwining music with STEM disciplines can foster a learning environment that encourages students to explore connections between disparate disciplines, promoting innovation and interdisciplinary and transdisciplinary learning. In addition, employing an HME-STEM philosophical construct in teacher preparation programs provides preservice teachers with innovative, creative curricular and instructional approaches for employing in PK-12 settings to support the cognitive and social, emotional needs of all PK-12 learners. The synergy of music and STEM affords learners rich curricular experiences at every education level (Table 4).

Table 4. The Synergy of Music and STEM across All Education Levels

Education Level	**Braiding Music and Threading STEM**
Early Childhood Education	Discriminating pitch, melodies Cognitive and social, emotional atmospheric learning Repetitive, rhythmic and melodic singing for neural processing Kinesthetics (dancing/clapping) for social bonding, communications, and emotional connections Phonological play through songs, rhymes, alliteration for sound of language Musical play immersion for self-expression, role adoption, and storytelling Simple technology and mathematics of counting and sound
Kindergarten	Basic Psychoacoustics for high and low sounds/pitch Basic musical notation, through rhythmic exercises, instruments, and singing Musical patterns and number sense through counting to music Apps and manipulative musical software and toys
Primary Education	Diatonic tone recognition within the seven notes of major or minor scales Musical instrument building and utilizing Phyphox app technology for sound wave experiments Sound, Waves, and Communication Systems (SWCS) programming for ICT-based learning for visual, textual, numeric and digital literacies Instrument design through blueprinting, constructing, and performing Science of sound waves, vibrations, fractions of musical notes, rests, and notation
Secondary Education	Hands-on and digitally-based curricula for physics of sound Sound engineering apps, handheld device, computers, etc., Technology for recording/manipulating soundwaves, producing creative works Advanced musical instrument engineering and construction Application of advanced mathematical concepts
Higher Education	Higher Music Education (HME) for artistic citizenship and cultural heritage Expressive learning through rhythm, melody, lyrics, and musical compositions Relationships of mathematics, neuroscience, and psychology of music Algorithmic composition and mathematical theories of music theory Advanced sound design, audio engineering, production Design engineering for acoustic environments

Conclusion

Resonant Reflections: Insights and Implications from Music-Driven STEM

This study threads processes of environmental physics through anatomical, physiological, and psychological mechanisms, including physical and cognitive science, neurophysiology, psychoacoustics, and cultural psychology for perceiving music. The interdisciplinary and transdisciplinary nature of music in STEM for STEAM education forms the foundation of authentic programmatic offerings for learners at all grade levels. This study highlights the transformative potential of interlacing music with STEM in early childhood through higher education settings. Interweaving music into STEM curricula enables educators to nurture critical thinking, creativity, and innovation among students. Creative and innovative approaches foster meaningful learning experiences for all learners and the development of emotive connections to the learning. A music and STEM for STEAM approach not only cultivates cognition, but also facilitates social and emotional learning. This research also emphasizes threading the art of music into tapestries of STEM education for developing comprehensive and engaging curricular offerings. Providing students with authentic, meaningful learning affords expressive curricula that resonates with learners and oscillates like cognitive strings, nurturing emotive symphonies of inquiry. The synergy of music in STEM possesses potential for shaping the future of education, fostering interdisciplinary collaboration, and nurturing the next generation of innovative thinkers and creative problem-solvers.

Recommendations

Composing Futures: At the Crossroads of Music and STEM Education

The researcher recommends threading music seamlessly into STEM for STEAM education across all levels, from early childhood through higher education. A music-STEM integration should be viewed not as an additional component, but as an integral part of authentic STEAM programs that bridge disciplinary boundaries and foster interdisciplinary and transdisciplinary connections. Incorporating music into STEM curricula cultivates critical thinking, creativity, and innovation among students, providing holistic learning experiences that intertwine cognitive development with emotional engagement.

It is also recommended that educators embrace creative and innovative teaching approaches that engage students in meaningful exploration and expression through synergetic music in STEM *and STEM in music* lessons. Providing opportunities for students to connect emotionally with content fosters deeper understanding and retention of complex concepts. Moreover, music's inherent ability to evoke emotions can serve as a powerful tool for promoting social and emotional learning alongside cognitive development.

The synergy of music in STEM education affords immense potential for shaping the future of learning. It is recommended that educators create dynamic and engaging, hands-on, experiential music-in-STEM learning environments that resonate with learners by nurturing students' intellectual curiosity for fostering the development of innovative thinkers and problem-solvers. A music-in-STEM approach holistically promotes interdisciplinary collaboration and empowers students at all grade levels to become active participants in the learning, resulting in student ownership of the learning and capitalizing on the cognitive and emotive aspects of music-in-STEM for meaningful STEAM erudition.

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