From Beat to Better: Exploring Music-Based Entrainment for Health

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ABSTRACT

Music has the increasingly recognized potential to promote physical and mental health, as evidenced by prior work on music engagement and its benefits on improved physical, cognitive, immune, and socioemotional functioning. However, the mechanisms underlying such effects still need to be better understood. One process that researchers have frequently quantified to understand these effects is music-based entrainment. This mapping review aims to (1) summarize evidence for the effects of music engagement in various health domains through intrapersonal and interpersonal entrainment and (2) identify open questions for future work. This review serves as a resource to inform the research priorities of health and music psychology experts who may be interested in evaluating and designing music-based psychosocial paradigms and health interventions.

1 Introduction

Music engagement has been explored extensively with health and social development. An expanding body of work demonstrates that music is being investigated more systematically as a potential non-pharmacological intervention for clinical populations. Active music engagement (i.e., the active participation of individuals in making or creating music, such as through singing or playing an instrument) is associated with various psychosocial health benefits. For example, singing in a choir may lead to greater subjective quality of life and social connectedness (Johnson et al., 2017). Learning a musical instrument early in life may promote the development of empathy and emotional competence (Kawase et al., 2018). On the other hand, passive music engagement (i.e., listening to music without actively participating in its creation or performance) has been shown to confer physical and mental health benefits, such as pain management, stress relief, and mood and exercise enhancement.

Although music has been used primarily as a cultural device for entertainment and religious purposes, it has a historical basis in medicine dating back to 400 B.C. (Babikian et al., 2013; Thaut, 2015). In ancient Greece, Pythagoras used music to treat bodily and psychological ailments. His younger contemporary, Plato, theorized that music therapy can attune the soul to the cosmos. Around the same time, Hippocrates, the father of medicine, was known to play music for his patients with mental illnesses.

Today, researchers have explored the effects of both active and passive engagement with music on health in multiple domains, including physical rehabilitation, pain management, cognitive and immune functioning, and psychosocial support (Chair et al., 2021; McCrary et al., 2021; Rodwin et al., 2023). Elements of music, including rhythm, tempo, pitch, timbre, and melody, influence human physiological and psychoemotional responses. For example, music has been found to arouse memory and association, stimulate imagery, evoke emotions, facilitate social interaction, and promote relaxation and distraction (Dileo, 2006). However, despite abundant reports of music's beneficial effects, there remains a limited understanding of the mechanisms underlying how active and passive music engagement impacts health domains.

To understand the effects of music on health, researchers have grounded investigations in a theoretical process called music-based entrainment. Entrainment, which can occur intrapersonally or interpersonally and is often used synonymously with the term "synchrony," is a phenomenon in which two or more independent rhythmic processes interact such that they adjust to each other in phase-locked coordination. Intrapersonal entrainment approaches measure the degree of coordination or synchrony between an individual's behavioral, neural, or physiological responses in a musical context or between their responses and musical features, such as tempo or rhythm. Indeed, intrapersonal music-based entrainment has been observed behaviorally and neurally, such as the coordination of interlimb movements (Mårup et al., 2022) or neural activation (Tierney & Kraus, 2015) with rhythmic structures in music. In contrast, interpersonal entrainment approaches involve measuring coordination between multiple individuals' behavioral, neural, and physiological responses in the presence of music or during music-making. For example, interpersonal entrainment has been observed in audience members' skin conductance responses and respiration rates during live musical performances (Tschacher et al., 2023). Figure 1 presents a schematic diagram of music-based interpersonal and interpersonal entrainment.

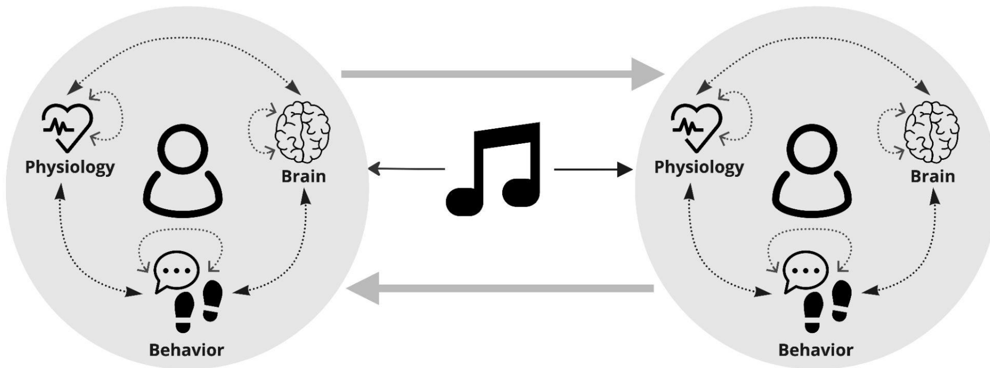

Figure 1. Schematic diagram of music-based intrapersonal and interpersonal entrainment. Grey circles encompass entrainment processes at the *intrapersonal* level, where each individual's behavioral and biological rhythms can entrain within or to each other and to music as an external pacer event. Grey arrows indicate the coordination of individual rhythmic processes at the *interpersonal* level.

Methodological approaches and findings from intrapersonal and interpersonal music-based entrainment studies may shed light on music's effects on various health domains observed in other studies. For instance, systematic reviews of music therapy and other music-based interventions have revealed their effectiveness in supporting emotional regulation and behavioral change (Rodwin et al., 2023). However, the explicit mechanisms by which such music-based interventions lead to their observed changes remain unclear. Models of entrainment, such as cross-correlations (Quan et al., 2023; Quian Quiroga et al., 2002) or cross-wavelet transform (CWT) analysis (Issartel et al., 2015), can be used to quantify the temporal synchronization or coherence between two time-series from, for example, musical structures and a behavioral response. These analytical tools enable researchers to examine the degree of temporal alignment of internal rhythmic processes to or in the context of music, supporting a more granular understanding of how specific components of a music-based intervention can impact physical, cognitive, and socioemotional domains within the self and with others.

Thus, this mapping review aims to synthesize and summarize the results of intrapersonal and interpersonal entrainment models for understanding how music engagement impacts various health domains. This review is a resource for health and music psychology researchers interested in designing and evaluating music-based psychosocial experiments and clinical interventions with clinical populations.

2 Methodology and Key Terms

The current paper employs a mapping review approach to categorize existing evidence on intrapersonal and interpersonal entrainment in music-based contexts to illustrate a potential mechanism underlying music engagement's effects on health in humans. In contrast to systematic reviews, mapping reviews employ a flexible and exploratory search strategy to gain a thematic understanding of the existing research on a specific topic, which includes evaluating potential gaps for future research to address (Grant & Booth, 2009). Three literature databases—Google Scholar, Web of Science, and PubMed—were selected based on their popularity in health and social sciences. They were inputted with variations of the following search term strings: music* AND entrainment OR synchron* OR coordinat*. Initial search results were screened on title and filtered down to articles including systematic reviews and empirical research studies published since 2013, given technological advancements in physiological measurement in the last decade. Exclusionary criteria encompassed articles not published in English or those not conducted on clinical populations. Articles included in this review encompassed any peer-reviewed empirical and intervention study that focused on clinical populations and music-based entrainment processes, including quantitative assessments of temporal dynamics between behavioral, neural, and physiological measures.

Before reviewing the literature, key concepts relevant to intra- and interpersonal music-based entrainment must be described. For this review, "music-based entrainment" encompasses any behavioral, neural, and physiological processes analyzed temporally within and between people during music engagement. The following subsections describe and provide examples of entrainment and musical rhythm and tempo from the literature.

2.1 Entrainment

Entrainment is a phenomenon in which two or more independent rhythmic processes interact, eventually entering phase-locked periodicity with each other (Clayton et al., 2005). The first conceptualization of entrainment was recorded in 1665 by Dutch physicist Christiaan Huygens, who described entrainment as "the sympathy of the clocks" (Korteweg, 1906), whereby two pendulum clocks would synchronize with each other within half an hour, even when one was deliberately perturbed. Later in the early 20th century, Appleton & Van der Pol (1921) laid important theoretical grounding for understanding nonlinear systems and their behaviors when they showed that the frequency of an oscillator could be entrained by a weak signal of a slightly different frequency.

Modern entrainment applications have since been extended to areas of biology and human social psychology. For example, photic entrainment is an essential property of the circadian clock that sets the appropriate timing of behavioral and physiological functions in plants and animals. When entrained, diurnal animals are active during the day and some plants exhibit heliotropism, the diurnal motion of plant parts in response to the direction of the sun (Foster & Kreitzman, 2005).

In human developmental and social psychology, most publications have routinely adopted the term "entrainment" to describe the coordination of human behavior and endogenous rhythms on both an intra- and interpersonal level. Table 1 provides an overview of different types of entrainment and an example observed at the intrapersonal and interpersonal levels for each type. The social entrainment model of McGrath & Kelly (1986) describes entrainment at these levels based on the following premises (Clayton et al., 2005):

(1) Across physiological, psychological, and interpersonal levels, human behavior is temporal and regulated by cyclical, oscillatory, and rhythmic processes.

(2) The regulatory processes are *endogenous* or inherent in the life processes of the organisms involved.

(3) The endogenous rhythms become mutually entrained to each other, acting in synchrony in phase and periodicity.

(4) The temporal patterns of individuals in interaction also become mutually entrained to one another.

(5) Collectively, the temporal patterns of individuals in interaction become entrained to certain external pacer events and entraining cycles, where the former alters the phase, and the latter changes the periodicity of the mutually entrained patterns.

While many works in social psychology and development have equated entrainment to synchronization, it is important to appreciate their distinction in the context of this review. Bittman (2021) asserts that "unlike entrainment, synchronization does not require even a single oscillator" (p. 196), as it describes the simultaneous occurrence of two or more events. Indeed, Clayton et al. (2005) define two basic components involved in any instance of entrainment: (1) there must be two or more autonomous rhythmic processes or oscillators, and (2) the oscillators must interact such that there is measurable interdependence between them. As follows, synchronization is not a necessary condition for entrainment. Still, it may occur over a broader range of periodicity—for example, the synchronous illumination of fireflies at dusk or covariations in respiratory and heart rates during physical exercise. This review focuses on such rhythmic processes that adjust to each other in phase-locked coordination within a musical context.

2.1.1 Intrapersonal

At the intrapersonal level, entrainment can occur when an individual's biological and behavioral rhythms coordinate with each other and an external pacer event, such as a musical beat. The entrainment of such rhythms may have implications for an individual's physical and cognitive functioning. For example, neural oscillations (i.e., rhythmic patterns of brain activity) can be entrained to an external rhythmic stimulus in a process known as neural entrainment. The functional role of neural entrainment is related to an individual's emotional responses (Grandjean et al., 2008), motor control (Buard et al., 2019; Te Woerd et al., 2018), and cognitive functions, such as attention (Calderone et al., 2014), perception (Kösem et al., 2018), speech processing (O'Sullivan et al., 2015; Peelle et al., 2013), and memory (Fell & Axmacher, 2011). Similarly, an individual's motor behaviors during physical exertion, such as running or pedaling, can be entrained to a rhythmic beat. This auditory-motor entrainment process is related to increased movement efficiency and respiration optimization (Bacon et al., 2012; Bood et al., 2013).

2.1.2 Interpersonal

At the interpersonal level, entrainment occurs when two or more individuals' social and biological rhythms become temporally coordinated. Studies in developmental psychology have shown that coordinated rhythms appear as early as infancy and play a crucial role in social development (Condon & Sander, 1974; Feldman, 2007; Jaffe et al., 2001). This human capacity to engage in complex and interdependent coordination with another in a mutually shared timeframe is associated with trust, empathy, and prosocial behavior (Cirelli et al., 2014; Launay et al., 2012; Rennung & Göritz, 2016). Such interpersonal characteristics facilitate social connectedness, a significant predictor of health and life expectancy. For instance, cancer survivors of advanced stages have recounted that strong social connections with family, friends, and medical staff increase their desire to live (Engebretson et al., 2014). Adolescent girls who feel more socially connected and to their school tend to have lower body mass indexes compared to those who feel less socially supported (Richmond et al., 2014). Although direct research on interpersonal coordination and long-term health outcomes is limited, findings from psychotherapy research allude to their positive association, specifically when interpersonal coordination of movement (Ramseyer & Tschacher, 2016), speech (Imel et al., 2014; Rocco et al., 2016), affect (Ramseyer, 2011), and physiology (Bar-Kalifa et al., 2019) were analyzed alongside therapeutic alliance and efficacy (Lo Coco et al., 2022).

2.2 Musical Rhythm and Tempo

Like many biological rhythms, music exhibits periodicity within a rhythmic framework. Due to its many time-varying features (harmony, tempo, phrasing, dynamics, etc.), music is engaging and thus captures attention more powerfully than other sensory stimuli (Brancatisano et al., 2020). Quantifying the temporal characteristics of human behavior and neural and physiological responses in the presence of music, rhythm, and tempo are often the variables of interest.

The simplest definition of tempo can be the rate or pace of events in an environment. In music, tempo communicates how fast or slow the piece is performed and, by proxy, the piece's overall emotion. Fast music tends to be perceived as "happy" and slow music as "sad" by both children and adults (Dalla Bella et al., 2001; Y. Liu et al., 2018; Mote, 2011). Mathematically, tempo is expressed as the rate of periodic events (i.e., beats) that listeners perceive to occur at regular temporal intervals, such as minutes (McAuley, 2010)—that is, beats per minute (bpm; see Figure 2).

Figure 2. An excerpt from the first movement of Mozart's Piano Sonata No. 11 in A Major, K. 331, in which the tempo is indicated by "Andante grazioso" (i.e., slow and graceful) and the modern editor's metronome marking "♪ = 120". Annotated red lines denote sequential, evenly-spaced beats. The rhythmic pattern in this excerpt comprises sixteenth, eighth, and quarter notes.

In music, rhythm is the most fundamental layer, without which melody cannot exist. Originating from the Greek word *rhythmos*, which means any regular recurring motion, "rhythm" is defined as the serial pattern of durations marked by sounds and silences (i.e., different types of notes and rests; see Figure 2). The temporal organization of such physical sound patterns is also commonly described with other musical characteristics, such as grouping, beat, and meter.

3 Results

Much of the existing work on music-based entrainment concerning health and intervention outcomes for clinical populations has been summarized in systematic reviews of music therapy and other music-based interventions (Sihvonen et al., 2017). While several studies are theoretically grounded in the concept of intrapersonal or interpersonal entrainment, only a small number of them directly measure the degree of entrainment to or within the context of music.

A total of 37 studies that met eligibility criteria for music-based entrainment research were identified for this review. The following subsections summarize the impact of music on clinical populations through intrapersonal or interpersonal entrainment processes across each study. Additionally, a selection of studies and their findings are discussed with respect to the inclusion or absence of quantitative entrainment measures. For reference, Tables 1 through 4 summarize each study based on the health subdomain addressed (i.e., physical rehabilitation, speech, language, and communication therapy, pain management, and mental and behavioral health). The tables also include the purpose of each study, the participant sample, musical entrainment-based approaches and measures, and relevant results.

3.1 Physical Rehabilitation

Most musical entrainment-based interventions for physical rehabilitation operate on rhythmic cueing with musical structures or rhythms, such as in patterned sensory enhancement or rhythmic auditory stimulation (Thaut & Hoemberg, 2014). Patterned sensory enhancement (PSE) is a neurologic music therapy (NMT) technique that takes advantage of musical patterns to structure and regulate movement patterns, especially those that are not rhythmical by nature (e.g., upper extremity flexion, grasping; Thaut & Hoemberg, 2014). In contrast, rhythmic auditory stimulation (RAS) involves the delivery of pulsed rhythmic or musical stimulation to improve motor functions that are rhythmical in nature, such as gait. While both PSE and RAS are NMT techniques with demonstrated positive results, RAS has undergone more extensive investigation and application in clinical populations. Studies of PSE interventions on upper extremity functioning have been conducted on children with cerebral palsy (Wang et al., 2013) and post-stroke patients (Kang et al., 2020). These investigations have revealed connections between enhanced function and the improved regulation of muscle activation patterns in the paretic limb. In contrast, RAS intervention studies have been conducted on more clinical populations, namely patients with post-stroke movement deficits (S. Lee et al., 2018; Mainka et al., 2018), Parkinson's disease (Bukowska et al., 2016; Calabrò et al., 2019; Capato et al., 2020; Cochen De Cock et al., 2021; Dalla Bella et al., 2015; Naro et al., 2020; Thaut et al., 2019), cerebral palsy (Efraimidou et al., 2016; Kim et al., 2020), and dementia (Wittwer et al., 2020). Some studies have revealed inconsistent results regarding improvements in specific gait parameters, such as stride variability (Harrison et al., 2019; Lirani-Silva et al., 2019), or when comparing auditory rhythmic cueing interventions to conventional physiotherapy (Gonzalez-Hoelling et al., 2021). However, most the literature on RAS for clinical populations have reported greater fall reductions and improvements in spatiotemporal gait characteristics such as velocity and stride length (Ghai et al., 2018; Yoo & Kim, 2016).

To the extent of the search performed for this review, a total of k = 15 studies investigating various musical entrainment-based interventions on n = 570 patients (394 with PD, 130 post-stroke, 46 with CP) and n = 79 controls were identified (Table 1). All of the studies implemented an intervention operating on rhythmic entrainment at the intrapersonal level. Among these, only four studies include a measure of music-based entrainment, such as beat perception or event-related EEG dynamics.

For example, in work by Georgiou et al. (2020), n = 11 post-stroke patients with hemiparesis and a mean age of 61.8 years underwent a RAS intervention delivered haptically via leg-worn wearable devices called Haptic Bracelets. Spatiotemporal gait characteristics were measured before, during, and after the intervention. While entrainment to rhythmic cues throughout the intervention was not measured, each participant's beat perception capability (i.e., beat entrainment) was visually and computationally assessed using a haptic tap test before the start of the intervention. Each participant's inclusion in the intervention was not dependent on their performance on the tap test. Overall, 55% of the participants improved temporal gait characteristics and 27% improved spatial gait characteristics. However, these findings are not interpreted with regard to participants' performances on the pre-intervention haptic tap test. Individual differences in beat perception (Grahn & McAuley, 2009; Schaefer & Overy, 2015) are important to consider and control for, given their potential to affect gait responses (Leow et al., 2014).

Similarly, Crosby et al. (2020) studied the responsiveness of n = 22 patients with post-stroke temporal gait asymmetry (TGA) to RAS and its relationship to rhythm ability. Participants were classified as “strong” or “weak” beat perceivers based on their accuracy scores on the Beat Alignment Test (BAT; Iversen & Patel, 2008) and underwent a RAS intervention that consisted of walking to the beat of a metronome in three trials. Additionally, each participant’s ability to match their footfalls to auditory cues was quantified using the interbeat interval deviation (IBD), calculated as the difference between the metronome’s mean interbeat interval and the participant’s mean interstep interval, divided by the interbeat interval. Accordingly, a lower IBD value indicates greater auditory-motor synchrony. Participants in the “strong” rhythm ability group showed significant improvements in TGA, while those in the “weak” rhythm ability group did not (they also showed high variability in TGA). No significant differences were found in IBD values between these two groups. Further, no interaction was found between TGA improvement and rhythm ability. However, the researchers emphasize that individual rhythm ability should be considered when delivering rhythm-based treatments to clinical populations.

Within the timeframe under review, existing studies on music-based interventions for movement rehabilitation in clinical populations cite entrainment at the intrapersonal level, and none have implemented an interpersonal paradigm. Further, more studies should include validation of their approaches by quantifying the degree of entrainment to music-based stimuli. Such validation measures of entrainment can include phase-matching performance (i.e., the extent to which the phase of steps matches the phase of beats) and period-matching performance (i.e., the extent to which the tempo of steps matches the tempo of beats). In addition, data on prior musical training or exposure (e.g., years of training outside of school-based music classes) can be collected to explain auditory-motor entrainment measures (Spiech et al., 2023). Researchers can refer to methodologies used in studies on individual differences in beat perception and rhythm ability for synchronization accuracy measures and their constraints (Crosby et al., 2020; Leow et al., 2014). In particular, these validation measures can be used to inform trajectories of rehabilitation outcomes in their treatments (Benoit et al., 2014). Those interested in designing an interpersonal paradigm for a music-based movement rehabilitation intervention can refer to existing work on interpersonal gait synchronization in healthy populations (Felsberg & Rhea, 2021).

3.2 Speech, Language, and Communication Therapy

In recent years, the integration of music into speech and communication rehabilitation programs has yielded positive results, harnessing music's inherent rhythm and melody to aid individuals in recovering language or improving their speech and communication skills. Most music-based interventions for speech, language, and communication impairments have been delivered as music therapy or music intonation therapy (MIT; Albert et al., 1973). More recently, auditory-motor mapping training (AMMT) has been developed and adapted from MIT (Chenausky & Schlaug, 2018). Favorable outcomes in expressive and receptive language and joint attention are reported in individuals with aphasia and those with autism spectrum disorder (Boster et al., 2021; Haro-Martínez et al., 2021; Q. Liu et al., 2022).

Music therapy (MT) for speech and communication involves the adaptation of musical elements, such as tempo, rhythm, and melody, to promote effective expressive and receptive language and communication skills by a trained music therapist (Hurkmans et al., 2012). This approach can be implemented actively, whereby the patient (or group of patients) engages in music-making, or passively, whereby the patient (or group of patients) listens to the music therapist who plays live or recorded music (Aldridge, 1994). Similarly, MIT is an evidence-based language treatment program that leverages musical elements like pitch (i.e., intonation of speech) and rhythm (e.g., tapping) to improve expressive language. MIT combines several facilitation techniques, including intoned speech, Sprechgesang (i.e., rhythmically emphasized prosody), unison production with the clinician, and lip-reading (Zumbansen et al., 2014a). Given the nature of these approaches, MT and MIT are inherently delivered at the interpersonal level in either one-to-one or group-based contexts.

Within the scope of the current review, $k = 7$ studies investigating the effects and mechanisms of MT and MIT on $n = 76$ individuals with speech and communication challenges (61 with autism or physical disability, 15 with post-stroke aphasia) and $n = 10$ controls were identified (Table 2). Among these, five studies explore interpersonal entrainment or synchrony in the context of MT in children with physical disability or autism spectrum disorder (Dvir et al., 2020; Nielsen & Holck, 2020; Samadani et al., 2021; Spiro & Himberg, 2016; Venuti et al., 2016), and two focus on intrapersonal rhythmic entrainment in post-stroke patients with aphasia during MIT (Curtis et al., 2020; Kershenbaum et al., 2019). Thus, music-based entrainment processes in speech, language, and communication therapy have primarily been investigated unimodally and interpersonally—for example, by interpretively annotating observable “synchrony” behaviors between therapists and patients or between children with disabilities and their parents. Further, among these studies, only two by Dvir et al. (2020) and Samadani and colleagues (2021) computed quantitative measures of dyadic synchrony in the context of music.

Dvir et al. (2020) sought to quantify the prevalence and characteristics of body movement synchrony in $n = 19$ therapist-child dyads across MT sessions held over a period ranging from 14 to 23 weeks. All children in the study were diagnosed with autism spectrum disorder (ASD) and between 4 and 6 years of age (mean age: 5.3 years). Therapist and child behavioral data were collected with video annotations of seven rhythm categories of the Kestenberg Movement Profile (KMP; Kestenberg Amighi et al., 2018). From each dyad's time-series data, the authors quantified synchrony using five attunement parameters that describe shared segments in which the therapist and child moved together in a similar rhythm, partially overlapping in time or following each other, as well as the mean lag (in seconds) for shared segments in which either partner followed the other's movement. For example, the Attunement Index was calculated as the ratio between the number of shared segments and number of total segments (shared and not shared). Results revealed higher attunement scores between therapists and children during high-frequency KMP rhythm categories (e.g., jumping), regardless of intensity. At the end of five months of treatment, no changes in autistic symptoms and children's ability to synchronize with therapists were observed. However, therapists were more synchronized with the children, as observed during segments in which the therapist's movements followed the child's ($Z = -2.3$, $p < .05$). The authors conclude that music therapists are able to use specific patterns of rhythmic movement to synchronize with children with ASD, while enhancing dyadic synchronization over multiple MT sessions. However, because no significant improvement in ASD symptoms were found after five months of treatment, the effectiveness of MT in reducing ASD severity in young children remains inconclusive.

While the former study investigated behavioral synchrony, Samadani and colleagues (2021) investigated neurophysiological synchrony in the context of MT between parents and nonverbal children with disabilities. In their study, $n = 10$ parent-child dyads, all of whom included nonspeaking children between the ages of 8 and 20 years (mean age: 14.7 years) and with severe motor impairments, participated in ten 15-minute MT sessions. During each MT session, electroencephalograms (EEGs) were collected from both parent and child to test the hypotheses that interbrain synchrony would be greater during MT than at baseline and that synchrony levels would increase throughout the MT session. Interbrain synchrony was quantified via parent-child EEG spectral coherence[1] and

[1] Spectral coherence quantifies the frequency-specific covariation between two signals and is given by the magnitude squared of their cross-spectral density over the product of their individual spectral densities (Bendat & Piersol, 2010).

Granger causality[2] measures and analyzed using a cluster-based permutation. Clusters were formed using only statistically significant cases with at least a Cohen's d of 0.5 from a rank sum test. In all dyads, the authors found increases in parent-child interbrain synchrony over an MT session, with greater coherence in contralateral frontal brain regions in the beta and gamma frequency bands. This study's findings suggest that parent-child alignment is responsive to MT, demonstrating that interbrain synchrony can be quantified and used to measure music-based treatment response.

Research on MIT in the last decade encompasses several studies investigating intervention mechanisms and their outcomes on individuals with aphasia, such as the use of rhythmic tapping or intonation alone or their combination (Zumbansen et al., 2014b) in treatment. While beat entrainment has been established as the theoretical basis for rhythm-based MIT, no studies to date employ a quantitative entrainment model to measure intrapersonal entrainment to rhythmic beats in patients. Nevertheless, aphasic patients' rhythmic abilities have been explored with their response to MIT treatment (Curtis et al., 2020; Kershenbaum et al., 2019). Curtis and colleagues (2020) investigated the rhythmic abilities of $n = 3$ post-stroke patients (mean age: 58 years) with regard to the effects of two 5-week MIT treatment blocks (i.e., with and without rhythmic tapping). All three patients had aphasia and apraxia of speech. Rhythmic ability was assessed with (1) the rhythmic contour subtest of the Montreal Battery of Evaluation of Amusia (MBEA; Peretz et al., 2003), (2) a task that required patients to tap along to short, repeated rhythms, (3) a memory-based tapping task from Zipse et al. (2014), and (4) a tapping-based subtest of the BAT (Iversen & Patel, 2008). One patient in the sample with impairments in both rhythmic ability and beat entrainment realized more significant gains during the MIT treatment without rhythmic tapping. The other two patients with unimpaired beat entrainment abilities realized more substantial treatment effects from MIT with rhythmic tapping. Overall, these findings suggest that rhythmic entrainment ability may help inform whether tapping should be included in MIT treatment for an individual. Specifically, assessing MIT candidates on beat entrainment ability and then customizing treatment protocols accordingly may help produce greater therapeutic effectiveness of MIT for those with impaired or weak entrainment abilities (Curtis et al., 2020). These results are similar to those found by (Kershenbaum et al., 2019), who also tested $n = 12$ adult patients with post-stroke aphasia on rhythmic ability using the MBEA and found that those who demonstrated greater rhythmic ability benefitted more from speaking

[2] Granger influence captures the directional influence of one time series on another (i.e., the degree to which future values of one time series are predicted by the combination of lagged values of itself plus those of a second time series (Granger, 1969).

rhythmically during MIT, compared to those who with weaker rhythmic ability. Overall, assessing patients' rhythmic abilities can help validate measures of effectiveness, such as response to treatment compared to controls, or inform the personalization of MIT treatment.

3.3 Pain Management

Like physical rehabilitation, most music-based interventions for acute and chronic pain management target an individual's capacity for intrapersonal auditory entrainment. Experimental studies on neural activity and pain show that an individual's neural oscillations in cortical and sub-cortical structures contribute to pain perception, particularly those in the theta (4–7 Hz), alpha (8–13 Hz), beta (14–29 Hz) and gamma (30–100 Hz) frequency bands (Peng et al., 2014; Ploner et al., 2017; Shao et al., 2012). Based on these findings, auditory neural entrainment has been suggested as a potential non-pharmacological treatment for acute and chronic pain (Maddison et al., 2023). Auditory neural entrainment leverages the simultaneous, binaural presentation of tones at differing frequencies (i.e., binaural beats), the difference of which results in an illusory tone to which neural oscillations entrain (Ingendoh et al., 2023; Karino et al., 2006). This neural phenomenon is the basis of the *brainwave entrainment hypothesis*, which posits that external stimulation (i.e., auditory or visual) at a specific frequency leads to brainwave oscillation at the same frequency or its multiples (T. L. Huang & Charyton, 2008). Thus, entrainment occurs unimodally and intrapersonally.

As summarized in Table 3, a total of $k = 7$ studies on $n = 663$ patients (601 undergoing surgery or endoscopy, 62 with chronic pain) were identified from the literature. All of the studies investigated the effects of an intervention based on neural entrainment, such as binaural beats (BB) or isochronically pulsed music. Only work by Merrill & Amin (2021) explored the use of music enhanced isochronically with pulsed theta-frequency tones in reducing self-reported pain and analgesic medication usage in patients with chronic pain. Among the studies investigating BB, two looked at the use of BB with patients experiencing chronic pain (Gkolias et al., 2020; Zampi, 2016), while the rest focused on patients undergoing surgery or endoscopy (Giordano et al., 2023; Olçücü et al., 2021; Schmid et al., 2020; Tani et al., 2022).

Across $n = 53$ adults (mean age: 41.7 years) with chronic pain (i.e., pain that lasts or recurs for longer than three months), work by Zampi (2016) and Gkolias et al. (2020) revealed a more significant reduction in perceived pain intensity with BB compared to placebo. Self-reports of pain were collected with either the common

11-point numeric pain rating scale (where a rating of "0" denotes no pain and a "10" denotes the worst pain) or a multidimensional chronic pain inventory.

Others have investigated the use of BB as a pain management tool in patients undergoing surgery or endoscopy. For example, Schmid et al. (2020) investigated the effects of a sensory stimulation intervention with BB using a head-worn audiovisual device, on minimizing sedative drug dose requirements during pediatric sub-umbilical surgery. Forty-nine boys with a mean age of 3 years were randomized to receive local anesthesia either with visual and BB stimulation or with no sensory stimulation. Compared to boys in the control group, who wore the same sensory stimulation device without it being activated, those in the intervention group were shown to require a smaller dose to maintain sedation during surgery. Similarly, Olçücü et al. (2021) investigated the effects of listening to BB, classical music, or no auditory stimuli on anxiety and pain levels in $n = 352$ male patients undergoing diagnostic cystoscopy (DC) or ureteral stent removal (USR) with local anesthesia. In both the DC and USR groups, listening to binaural beats had a stronger effect on lowering self-reported pain on a visual analog scale than listening to classical music or no auditory stimuli.

Together, these studies point to the potential of neural entrainment processes mediated with frequency-specific tones as pain management tools. Nonetheless, these studies did not include entrainment measures because the researchers did not use electrophysiological measures or analytical techniques to quantify brainwave-stimuli synchrony. Thus, the mechanisms underlying how frequency-based sensory stimulation translates into psychophysiological changes are still unknown (Garcia-Argibay et al., 2019).

While the aforementioned studies investigate interventions leveraging an intrapersonal, unimodal level of music-based entrainment, other explorations into music as an analgesic have studied its effects bimodally (Werner et al., 2023) and interpersonally (Sullivan & Blacker, 2017; Tarr et al., 2016). However, bimodal and interpersonal paradigms of music-based entrainment have yet to be carried out on clinical populations dealing with pain. Future work employing such paradigms can look to exemplar studies summarized herein.

Werner et al. (2023) investigated the impact of sensorimotor synchronization to music on pain perception in $n = 59$ healthy adults (mean age: 22.2 years). Participants underwent a series of four experimental conditions featuring either music or silence, with or without tapping their foot, during which pain stimuli were delivered to the participant's fingernails via pressure algometry. Participants were then asked to rate their perceived pain on a 9-point Likert scale. Listening to music with tapping had a more substantial effect (d = 0.93) on reduced pain than sitting in silence without tapping. Additionally, sitting silently while tapping was not associated with lowered pain ratings. These results suggest that the bimodal combination of motor and passive music engagement is associated with an analgesic response. However, the degree of music-tapping synchronization (i.e., tapping to the beat of the music) is unclear, as participants' rhythmic abilities were not measured. For example, the ability to maintain rhythm via tapping can be evaluated by assessing the similarity of consecutive inter-tap intervals, as in the work by Crosby et al. (2020), within a synchronization-continuation paradigm (Madison, 2001).

At the interpersonal level of entrainment, Sullivan & Blacker (2017) and Tarr et al. (2016) explored how different types of music-based synchrony affect pain thresholds in healthy adults. In both studies, synchrony variables were manipulated by task, not on a continuous scale. In Sullivan & Blacker (2017), synchrony levels were manipulated by instructing n = 30 participants (mean age: 20.4 years) to drum to the beat of a metronome by themselves or with a partner in in-phase or anti-phase synchrony conditions. The in-phase condition required partners to drum to the metronome beat together, while the anti-phase condition required them to drum to the down- and upbeats of the metronome. Similarly, Tarr et al. (2016) used a silent disco paradigm to manipulate various behavioral synchrony conditions, where n = 94 participants (mean age: 24.3 years) were asked to dance synchronously, partially synchronously (i.e., counterbalanced movements with the same music), and asynchronously (i.e., unique movements with different music) to each other in groups of four. Both studies revealed that, in general, interpersonal musical engagement has a more significant analgesic effect than solo musical engagement. However, while Tarr et al. (2016) found that those who danced in synchrony experienced elevated pain thresholds, Sullivan & Blacker (2017) found that drumming in anti-phase synchrony produced a greater pain threshold change. Together, findings from these studies suggest that multiple mechanisms (e.g., differences in attention, sensorimotor coordination, or rhythmic ability) and types of musical engagement (e.g., active versus passive) may contribute to the analgesic effect of music-based interpersonal synchrony.

3.4 Mental and Behavioral Health

Numerous studies indicate positive associations between music engagement and psychosocial factors, suggesting that music may protect against psychological issues (Gustavson et al., 2021). While some research suggests that professional musicians are at elevated risk for internalizing problems such as neuroticism (Jonas Vaag et al., 2018), anxiety (Niarchou et al., 2020; Wesseldijk et al., 2019), and burnout (Wesseldijk et al., 2019), the overall body of work predominantly underscores positive associations between music engagement and psychosocial indicators. For example, active engagement in music, such as singing or playing an instrument, tends to be associated with greater subjective quality of life and satisfaction with health (Johnson et al., 2017; Løkken, 2017). Musical training, which can facilitate the development of sensitivity to emotional content in speech and vocalizations (Kraus & Chandrasekaran, 2010; Parsons et al., 2014), has also been suggested to help develop and maintain empathy and emotional intelligence, an important construct related to prosocial behavior and altruism (Eisenberg & Miller, 1987; Kawase et al., 2018; Roberts & Strayer, 1996; Theorell et al., 2014). Similarly, passive engagement confers psychosocial benefits. For instance, in young female adults, listening to music is effective in reducing premenstrual symptoms, particularly depressive and anxious symptoms (Setareh et al., 2017; Solt Kırca & Kızılkaya, 2022). Other reductions in self-reported anxiety with music have also been reported in healthy populations (B. Huang et al., 2021) and those awaiting or in surgery (Bradt et al., 2013; Nichols, 2015). In healthcare contexts, music medicine (MM), which involves listening to music as administered by medical personnel, has become an established method of alleviating preoperative anxiety in patients.

In light of the compelling evidence on the psychological benefits of music, interventions with music have been developed and tested for psychosocial problems such as anxiety, depression, and stress in clinical contexts (de Witte et al., 2022; Lu et al., 2021; Tang et al., 2020). Music-based interventions for psychosocial health are predominantly administered by medical or healthcare professionals in music medicine and trained music therapists in MT. Whereas MT is primarily a personally tailored rehabilitation approach delivered by a therapist, MM provides prerecorded music (e.g., classical music, binaural beats) through headphones, musical pillows, or background sound systems.

Within the scope of this review, k = 8 studies exploring musical entrainment processes concerning psychosocial outcomes in n = 472 participants with clinically significant depressive or anxious symptoms were identified from the literature (Table 4). Intervention approaches of these studies tend to overlap with those of studies targeting pain management, as many are based on rhythmic or beat entrainment (Fallek et al., 2020; Földes et al., 2017; Mallik & Russo, 2022; Weaver et al., 2020). Others have evaluated stress, depression, and quality of life scores in relation to interventions with musical entrainment activities such as chorusing, clapping, or dancing (Y. J. Lee et al., 2020) or stimuli enhanced with entraining elements such as binaural tones or flickering lights (Braun Janzen et al., 2019; Daengruan et al., 2021; Pino, 2021). Yet none of these studies directly quantify entrainment with physiological measures and an entrainment model or sufficiently control for musical (e.g., rhythm, tempo, melody) or study protocol (e.g., interpersonal versus intrapersonal) characteristics.

For example, Földes and colleagues (2017) sought to determine whether the synchronization of external auditory stimuli during a magnetic resonance imaging (MRI) scan would relate to reductions in self-reported anxiety. Specifically, they evaluated whether synchronization of musical stimuli to the MRI scanner's gradient pulsation improves music's relaxation effect for $n = 60$ adult outpatients (mean age: 47.2 years). Patients were randomly assigned to three groups—a control group (i.e., headphones or earplugs with no music playing), a *random* group (i.e., headphones with a prechosen playlist of music), and a *synchronous* group (i.e., headphones with the same playlist of songs but with their tempos manually modified to the tempo of the MRI scanner's pulsations). Tempo modification for beat synchronization with the MRI was achieved using MAX7, a multimedia graphic programming platform for creating MIDI, audio, and graphics applications. State-trait anxiety (pre- and post-scan), claustrophobia (post-scan), and experience with the MRI scan (post-scan) were measured using self-report questionnaires. Results of the study demonstrated that, while music listening significantly decreased state anxiety levels after the MRI scan in the *random* and *synchronous* groups compared to the control group, there was no difference in effects on anxiety level of the *random* and *synchronous* music. Although beat entrainment was controlled for via stimulus manipulation in this study, patients' rhythmic perception abilities were not measured to explain, for instance, whether beat perception ability moderates anxiety reduction. Further, the design of this study targets neither intrapersonal nor interpersonal entrainment, and the study participants are assumed to be able to engage with entrained auditory stimuli passively.

Similarly, a recent study by Pino (2021) aimed to reduce self-reported anxiety and depression scores in $n = 15$ adults (mean age: 49.3 years) with anxiety and depressive disorders using an EEG-based brain-computer interface (BCI) intervention in an 11-week-long randomized controlled trial. In the experimental group, visual stimuli of flickering lights were entrained to participants' brain rhythms during a presentation of musical stimuli via the BCI system. Self-reported anxiety and depression scores were obtained via the State-Trait Anxiety Inventory (STAI; Spielberger et al., 1983) and the Hamilton Rating Scale for Depression (HAM-D; Hamilton, 1960). In each 45-minute session, participants in the experimental group were instructed to sit comfortably in a chair while wearing the NeuroSky Mindwave EEG headset and direct their gaze toward the visual effector. Those in the control group were invited for individual psychoeducation sessions with face-to-face interaction and videos. Overall, the results of this study indicate that variations in EEG spectral power during audio-visual stimulation are related to changes in HAM-D and STAI scores. Specifically, variations in beta frequency bands were associated with a reduction in HAM-D scores, while reductions in alpha bands predicted an increase in STAI scores. Given the black box model of the NeuroSky headset that outputs a user's specific mental states while being worn, whether such mental states result from neural entrainment to musical stimuli remains unclear. Indeed, Pino (2021) acknowledged that future work should examine the relationship between musical structures and participant engagement to observe neural entrainment using an EEG system with higher spatial resolution.

4 Discussion

This mapping review summarizes results of intrapersonal and interpersonal music-based entrainment in the context of health and intervention outcomes in physical rehabilitation, speech-language and communication therapy, pain management, and mental and behavioral health. While the studies reviewed are grounded in intrapersonal or interpersonal entrainment processes, only a limited number directly measure the degree of entrainment within the context of music. Additionally, music-based entrainment is explored more often unimodally at the intrapersonal level, with much fewer studies using multimodal measures or interpersonal paradigms. Such models of entrainment can offer insights into the complex interplay among neural, behavioral, and physiological processes and the interpersonal social dynamics underlying how music impacts health.

Most music-based interventions have been delivered and evaluated at the intrapersonal level of entrainment, particularly for physical rehabilitation, pain management, speech and communication therapy, and psychosocial health. These intervention studies have shown the beneficial effects of passive engagement with music on patients with gait abnormalities, chronic or acute pain, and speech and communication impairments, as well as on patients' preoperative anxiety levels. Passive musical engagement, such as listening to binaural beats or rhythmic cues, leverages the unimodal entrainment of brainwaves to specific frequencies or of the auditory-motor system to rhythmic beats. Such entrainment processes are thought to underlie the therapeutic effects of music in these domains. However, the use of quantitative entrainment models in these intervention studies appears limited and should be incorporated into future studies to increase their internal validity, while supporting a more granular understanding of the mechanisms underlying intervention outcomes.

Presently, research in this field typically evaluates entrainment in cases where interventions involve rhythmic cueing within an intrapersonal framework, such as stepping to the beat of a metronome for gait rehabilitation or tapping during music intonation therapy for language recovery. They do not investigate beat perception during the interventions. To increase the validity of patients' performance measures in such rhythm-based interventions, synchronization accuracy during the intervention should also be considered. Further, quantitative measures of rhythmic entrainment or synchronization can allow custom tailoring of music-based interventions, thereby increasing overall intervention effectiveness.

Despite the promising outcomes reported in various intervention studies, it is important to acknowledge existing gaps in these studies that pertain to the quantification of entrainment and the adequate control of musical and study protocol variables. Future investigations should strive to establish a more rigorous methodology, enabling a clearer understanding of the intricate relationship between musical entrainment and health-related outcomes in clinical populations.

Given the wealth of research pointing to the potential of music to help manage and improve clinical symptoms, the National Institutes of Health is now promoting rigorously designed, well-powered clinical trials of music-based interventions (Edwards et al., 2023). Clinical researchers can look to prior studies with non-clinical population samples and adopt similar methodological approaches, including using entrainment models to measure the temporal synchronization of neural, physiological, and behavioral indicators to each other or to musical structures. These models can also be expanded to explore multimodal coupling effects (Namazi et al., 2021) or interpersonal dynamics and their effects within a music-based intervention—for example, how interpersonal musical engagement is associated with an analgesic response (Sullivan & Blacker, 2017; Tarr et al., 2016). Such dynamics in music-based interventions can be quantified using models with parameters that demonstrate temporal, morphogenic, and phasic interdependencies in synchrony (Levenson, 2024), including magnitude, sign, direction, lag, and timing (Palumbo et al., 2016). Depending on the parameters used in their analyses, researchers can address a variety of research questions, such as how strong the interpersonal synchrony of two individuals is in a musical context, or whether their behaviors or physiologies move in the same direction or away from each other, or behind or ahead of the other. As the field continues to evolve, collaborative efforts among clinicians and researchers in neuroscience, psychology, and music cognition will be needed to refine and expand the study and application of music in health interventions to include intrapersonal and interpersonal mechanisms of action.

Table 1. **Music-Based Entrainment Studies for Physical Rehabilitation Since 2013 (k = 15 studies; n = 649 participants)**

Study	Entrainment Process	Entrainment Measure	Purpose	Sample	Outcomes
Wang et al. (2013)	PSE	None	Investigate the effect of a 6-week exercise intervention with PSE music on gross motor functioning, mobility, and walking speed in children with CP.	36 children with spastic CP (18 with PSE music; 18 with no music)	The PSE group showed greater improvements in overall gross motor functioning, compared to the no-music group. No improvements were found in mobility or walking speed.
Dalla Bella et al. (2015)	RAS	Beat perception	Investigate across two studies the effects of musically cued gait training (MCGT) on (1) gait kinematics and (2) perceptual and motor timing in PD.	15 adult patients with PD; 20 healthy adults	11 out of the 15 patients with PD improved in uncued gait speed and stride length after MCGT. Response to MCGT was related to beat perception ability and improved perceptual and motor timing at 1-month follow-up.
Bukowska et al. (2016)	RAS; PSE	None	Evaluate the combination of RAS, PSE, and TIMP[a] on improving gait and other rhythmical activities in PD rehabilitation.	55 adult patients with PD (30 experimental; 25 control)	The combination of RAS (metronome), PSE (rhythmic music), and TIMP (percussion instruments) improved the majority of spatiotemporal gait characteristics in the experimental group, compared to the control group.

Efraimidou et al. (2016)	RAS	None	Examine the effects of an 8-week RAS intervention on gait, balance, and psychological indicators.	10 athletes with spastic CP (5 intervention; 5 control)	The intervention group improved in measures of gait, balance, mood, and self-esteem, while the control group did not.
Lee, Lee, and Song (2018)	RAS	None	Investigate the effects of six weeks of 60-minute gait training with bilateral RAS on lower extremity rehabilitation.	44 post-stroke patients (23 intervention; 21 control)	The intervention group demonstrated greater improvements in gait symmetry and ability, balance, and lower extremity function than at baseline and the control group.
Mainka et al. (2018)	RAS	None	Evaluate the efficacy of the treadmill training with RAS (RAS-TT), compared with conventional treadmill training (TT) and a neurodevelopmental treatment based on the Bobath approach (NDT), on functional gait.	35 post-stroke patients with lower-limb hemiparesis and gait asymmetry (11 RAS-TT; 13 TT; 11 NDT)	RAS-TT showed greater efficacy in restoring functional gait than conventional TT and NDT approaches.
Calabrò et al. (2019)	RAS	EEG event-related desynchronization (ERD) and synchronization (ERS); gait cycle-related frequency-band coherence	Identify neurophysiological mechanisms underlying gait improvement in PD patients undergoing an 8-week RAS intervention.	50 adult patients with PD (25 RAS; 25 non-RAS)	RAS training enhanced functional gait, fall self-efficacy, PD severity ratings, and overall gait quality compared to non-RAS training. RAS also increased EEG power and frontocentroparietal/temporal connectivity more than non-RAS training.

Harrison, Horin, and Earhart (2019)	Other musical cueing	None	Explore the effects of external and internal rhythmic cueing (i.e., mental or out-loud singing) techniques at varying tempos on gait.	30 adult patients with PD; 30 healthy adults	All participants demonstrated changes in gait velocity in response to different tempos. External auditory cueing with music increased gait variability, while internal cueing decreased gait variability relative to uncued walking.
Lirani-Silva et al. (2019)	RAS	None	Examine the effect of auditory cues on gait characteristics on people with early PD at two time-points, three years apart.	25 adult patients with PD (9 patients in the follow-up); 29 healthy older adults	Both groups showed improvements in step velocity, length, and time with RAS. However, there was an increase in step time variability across both groups. Step velocity and length was improved at the 3-year follow-up.
Capato et al. (2020)	RAS	None	Study the treatment and maintenance (at 1- and 6-month follow-ups) effects of a 5-week multimodal balance training with and without RAS.	154 adult patients with PD (56 RAS; 50 non-RAS; 48 control)	RAS-supported balance training was more effective than non-RAS training. Compared to controls, patients in both RAS and non-RAS training groups showed and maintained balance improvements at 1-month follow-up. Only the RAS group maintained intervention effects at 6-month follow-up.

Cochen de Cock et al. (2021)	RAS	None	Evaluate the observance, safety, tolerance, usability, and enjoyment of an individualized musical stimulation system called "BeatWalk" for at-home gait rehabilitation.	45 adult patients with PD	Patients used the system for an average of 78.8% of the prescribed duration. 75% of the patients found it easy to use. Overall quality of life, fear of falling, and gait parameters during an uncued 6MWT improved between pre- and post-intervention.
Crosby et al. (2020)	RAS	Beat perception	Study the relationship between rhythm ability and gait performance of post-stroke patients in walking trials with and without auditory cues.	22 post-stroke patients with temporal gait asymmetry (TGA)	RAS was more effective for post-stroke TGA patients who had strong beat perception than for those who had weak beat perception.
Georgiou et al. (2020)	Other musical cueing	Beat perception	Study the effects of RHC delivered with haptic bracelets on spatiotemporal gait characteristics.	11 post-stroke patients with lower-limb hemiparesis	All patients improved in temporal gait characteristics, and half improved in spatial characteristics with RHC.
Kang et al. (2020)	PSE	None	Examine the effects of no auditory, rhythmic auditory, and melodic auditory cueing on post-stroke upper limb functioning.	18 post-stroke patients with upper-limb hemiparesis	Melodic auditory cueing delivered the greatest improvement across all parameters of upper limb functioning, compared to no auditory or rhythmic cueing. Pitch contour may provide more information about upper-limb kinematic phases for the patient.

Naro et al. (2020)	RAS	None	Explore the effects of a monthly RAS-supported gait training within a conventional physiotherapy program on Parkinsonian gait performance and related EEG dynamics.	20 adult patients with PD (10 with deep brain stimulation [DBS]; 10 without DBS)	RAS-supported training combined with conventional physiotherapy improved gait in PD patients, with greater results in those who received DBS. Enhanced outcomes were linked to stronger beta oscillation remodulation in patients who received DBS.

Note. CP = Cerebral palsy; EEG = electroencephalography; PD = Parkinson's disease; PSE = Patterned sensory enhancement; RAS = Rhythmic auditory stimulation; 6MWT = six-minute walk test. "Other musical cueing" includes approaches involving cueing motor production with music and rhythmic beats through other modalities (e.g., mental singing, haptic feedback).

[a] Therapeutic Instrumental Music Performance (TIMP) is a neurologic music therapy technique that employs musical instruments as a way to simulate and facilitate functional movements to improve range of motion, limb coordination, postural control, etc.

Table 2. **Music-Based Entrainment Studies for Speech, Language, and Communication Since 2013 (*k* = 7 studies; *n* = 86 participants)**

Study	Entrainment Process	Entrainment Measure	Purpose	Sample	Outcomes
Spiro & Himberg (2016)	Therapist-child physical and gestural dynamics	None	Develop an annotation protocol and tools to accumulate large datasets of MT for the analysis of interaction dynamics underlying changes in communicative behaviors with MT.	5 therapist-child dyads with autism, except one with non-specified communication disorder	The video annotation protocol demonstrated high interrater reliability, but low feasibility given its time-consuming nature. Shared rhythmic pulse alternated with mutual therapist-child facing was related to musical structure.
Venuti et al. (2016)	Therapist-child behavioral and emotive states of synchrony	None	Verify with observational quantitative measures the efficacy of improvisational MT treatment in increasing the synchronic ability of children with ASD.	25 therapist-child dyads with autism	During the MT cycle, there is more synchronized activity, with a noticeable increase in dyadic synchrony from session 1 to session 20, as demonstrated in regression models with ADOS scores for the 'anticipation of a routine with objects' activity.

Kershenbaum et al. (2019)	Unison production with an auditory model in MIT	Temporal Organization subtests of the Montreal Battery of Evaluation of Amusia	Investigate the role of unison production in singing and rhythmically speaking unfamiliar lyrics on syllable accuracy in patients with aphasia.	12 adult post-stroke patients with aphasia; 10 age-matched neurotypical adults	Unison production with rhythmic speech is more effective for syllable accuracy than solo production and singing in MIT. Those with poorer perceptual rhythm ability benefited more from singing than rhythmic speech.
Curtis et al. (2020)	Rhythm-based MIT	Rhythmic ability batteries	Investigate rhythmic ability with response to two 5-week MIT treatment protocols with and without rhythmic tapping.	3 post-stroke patients with aphasia	Intact rhythmic ability is associated with response to MIT protocols with rhythmic tapping. Rhythmic entrainment ability can be used to inform the personalization of MIT treatment protocols.
Dvir et al. (2020)	Therapist-child rhythmic movement synchrony	Shared, child-leading, and therapist-leading attunement indices	Quantify the prevalence and characteristics of attunement during MT to understand the synchronization of music therapists with children with autism.	19 therapist-child dyads with autism	Higher therapist-child attunement values were observed during high-frequency KMP rhythm categories (e.g., jumping), regardless of intensity. At the end of the treatment, no changes in autistic symptoms and children's ability to synchronize with therapists were observed; however, therapists were more synchronized.

Nielsen & Holck (2020)	Therapist-child inter-subjective relating	None	Characterize synchronicity in the context of intersubjective relating during improvisational MT.	1 five-year-old boy with autism	Three types of synchronicity (i.e., therapist-initiated, child-initiated, and co-creation of shared rhythmicity) were identified with regards to different levels of intersubjectivity.
Samadani et al. (2021)	Parent-child interbrain synchrony	Spectral coherence; Granger causality	Measure the presence of and change over time in neurophysiological synchrony underlying parent-child socioemotional connection during MT.	10 parent-child dyads with disability	Dyadic spectral coherence was observed between child frontal right and parental frontal left regions at beta and gamma frequency bands in empathy-related brain regions. Granger influences were detected bidirectionally between parent and child in same frequency bands. Session-specific spectral coherence and Granger influences increased over time.

Note. KMP = Kestenberg Movement Profile. MT = music therapy; MIT = music intonation therapy.

Table 3. **Music-Based Entrainment Studies for Pain Management Since 2013 (*k* = 7 studies; *n* = 663 participants)**

Study	Entrainment Process	Entrainment Measure	Purpose	Sample	Outcomes
Zampi (2016)	BB	None	Assess the effects of theta-frequency binaural beats on perceived pain.	32 adults with self-reported chronic pain	Changes in average perceived pain between pre- and post-intervention showed a 77% larger drop for the theta BB intervention than for placebo.
Gkolias et al. (2020)	BB	None	Evaluate whether a one-week theta-frequency BB intervention can decrease pain perception and analgesic medication use.	21 adult patients with chronic pain[a]	Perceived pain ratings were significantly reduced during the first 30-min phase and week's end of BB intervention, compared to placebo (i.e., non-binaural tone at 400 Hz). Stress was reduced in both interventions and remained reduced at week's end of only the BB intervention. Analgesic medication consumption was significantly less during week of the BB intervention.
Schmid et al. (2020)	BB with visual stimuli	None	Evaluate the influence of brainwave entrainment on minimizing sedative drug dose requirements during surgery.	49 boys undergoing sub-umbilical surgery with regional anesthesia	The entrainment intervention group required less sedative drug dosing during surgery, compared to the control group.

Merrill and Amin (2021)	Isochronically pulsed sounds	None	Investigate whether self-chosen music with rhythmically enhanced beats can reduce perceived pain and analgesic medication usage.	9 adults with chronic pain[a]	Compared to no listening, the intervention with isochronic beats resulted in a 26% reduction in mean change in numerical pain scores and a 60% reduction in analgesic medication dosage.
Ölçücü et al. (2021)	BB	None	Investigate the effects of pure BB on anxiety and pain scores in male patients undergoing surgical procedures with local anesthesia.	209 male patients undergoing diagnostic cystoscopy (DC); 143 male patients undergoing ureteral stent removal (USR)	In both the DC and USR groups, listening to BB had a stronger effect on lowering self-reported pain on a visual analog scale than listening to classical music or no auditory stimuli.
Tani et al. (2022)	BB	None	Determine the effect of BB on pain perception and comfort during colonoscopy without sedation.	90 colonoscopy patients (42 with BB; 48 control with white noise)	Retrospective ratings of pain and comfort during the procedure were higher in the experimental group than in the control group.
Giordano et al. (2023)	Musically entrained breathing during MT	None	Investigate the effects of MT intervention on anxiety, pain, and satisfaction in patients undergoing percutaneous renal biopsy (PRB).	80 patients undergoing renal biopsy (40 MT, 40 control)	The MT group showed lower anxiety and pain scores than control group after PRB. Heart rate variability revealed decreased sympathetic and increased parasympathetic activity in the MT group.

Note. BB = binaural beats; MT = music therapy.

[a] Chronic pain was defined as any pain that lasts or recurs for longer than three months.

Table 4. **Music-Based Entrainment Studies for Mental and Behavioral Health Since 2013 (*k* = 8 studies; *n* = 472 participants)**

Study	Entrainment Process	Entrainment Measure	Purpose	Sample	Outcomes
Földes et al. (2017)	Tempo-adjusted music	None	Test whether listening to music synchronized to MRI device pulsations can reduce anxiety levels after the imaging scans.	60 adult patients undergoing MRI scans (20 with synchronized music; 20 with regular music; 20 controls)	Music listening reduced post-exam anxiety in both listening groups, unlike white noise in the control group. No differences in anxiety levels were found between the synchronized and regular music groups. Participants in both music groups found the MRI experience more pleasant than the control group.
Braun Janzen et al. (2019)	Music enhanced with binaural tones	None	Evaluate the effects of a 5-week music listening intervention with rhythmic sensory stimulation on depression and anhedonia.	19 patients with MDD and currently experiencing a MDD episode	Significant changes from baseline in measures of depression and associated symptoms, including sleep quality, quality of life, and anhedonia were found.

Fallek et al. (2019)	Musically entrained breathing	None	Investigate the feasibility and effectiveness of MT for in reducing anxiety in patients in palliative care, transplantation, medical intensive care, and general medicine.	150 adult patients	The most commonly requested intervention involved music-assisted relaxation and breath entrainment. Patients experienced reduced anxiety after the sessions. MT was found to be a flexible and easily accepted intervention, with patients showing strong interest, openness, and satisfaction.
Lee, Kim, & Park (2020)	Musical entrainment activities (e.g., dancing, singing)	None	Examine the effects of an 8-week laughter program with entrainment music on stress, depression, and quality of life among gynecological cancer patients.	36 adult gynecological cancer patients (17 intervention; 19 controls)	The intervention group using entrainment music exhibited a noticeable improvement in their overall stress, depression, and quality of life scores, relative to the control group.
Weaver et al. (2020)	Tempo-adjusted music	None	Investigate the benefits of rhythmic entrainment intervention on anxiety levels prior to diagnostic imaging.	1 adult patient with multiple myeloma	Pre- and post-session measurements of blood pressure, heart rate, state trait anxiety an increase in relaxation and decrease in anxiety level. Behavioral observations included eyes closing, ceasing fidgeting, and facial muscles relaxing during the intervention.

Daengruan et al. (2021)	Music enhanced with binaural tones	None	Assess the effectiveness of MT with BB to reduce depressive symptoms and improve quality of life and medication adherence in MDD patients.	18 adult patients with MDD (9 intervention; 9 controls)	No significant effects of MT were found on depression, quality of life, and medication adherence scores.
Pino (2021)	Audiovisual stimulation	None	Explore the efficacy of a BCI prototype with audio-visual stimulation aimed at neural entrainment.	25 patients with depression and anxiety (12 intervention; 12 controls)	There was a significant reduction in depression scores in the intervention group. Variability in depression scores were explained by changes in beta-1, beta-2, and delta frequency bands.
Mallik & Russo (2022)	Music enhanced with specific tones	None	Examine the calming effect of music combined with ABS on individuals with anxiety.	163 participants taking anxiolytics (39 music + ABS; 36 music only; 41 ABS only; 47 controls)	Greater reductions in somatic anxiety were observed in the "music +ABS" and "music-only" groups than in controls with moderate anxiety. No significant differences were observed among the treatment conditions for patients with high anxiety.

Note. ABS = auditory beat stimulation; BCI = brain-computer interface; MDD = Major depressive disorder; MRI = magnetic resonance imaging; MT = music therapy.

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