Annals of the New York Academy of Sciences

ANNALS OF THE NEW YORK ACADEMY OF SCIENCES

CONCISE REVIEW

From Finger Taps to Footsteps: Gait as a Model for Investigating and Training Rhythmic Abilities

Clara Ziane[1,2,4] | Simone Dalla Bella[1,3,4,5]

[1]International Laboratory for Brain, Music and Sound Research (BRAMS), Montreal, Quebec, Canada | [2]School of Kinesiology and Physical Activity Sciences, University of Montreal, Montreal, Quebec, Canada | [3]Department of Psychology, University of Montreal, Montreal, Quebec, Canada | [4]Centre for Research on Brain, Language and Music (CRBLM), Montreal, Quebec, Canada | [5]VIZJA University, Warsaw, Poland

Correspondence: Clara Ziane (clara.ziane@umontreal.ca) | Simone Dalla Bella (simone.dalla.bella@umontreal.ca)

Keywords: auditory–motor synchronization | finger tapping | gait | rehabilitation | rhythmic abilities

ABSTRACT

Synchronization of movements to auditory rhythmic cues, such as music or metronomes, often occurs spontaneously. Nonetheless, important interindividual differences exist in auditory–motor synchronization (AMS). Effects of rhythm on movements are partly modulated by rhythmic abilities, which include beat perception, motor production, and sensorimotor integration. These rhythmic abilities are often assessed using finger-tapping tasks, which can be performed in highly controlled environments and are easy to implement. In this article, we present limitations associated with finger-tapping tasks and propose gait as an alternative model for investigating and training rhythmic abilities. We focus on three key elements that differentiate gait from tapping and are critical in assessing AMS: the need to coordinate multiple effectors, emergent timing associated with continuous actions, and movement automaticity. Interestingly, cued–gait interventions (i.e., walking to rhythmic auditory cues for several weeks) have shown positive effects on all aspects of rhythmic abilities, while tapping interventions (e.g., playing tablet-based serious games) might lead to more limited transfer. In sum, gait offers a functionally rich behavioral model that can capture the complexity and ecological validity necessary to study and train AMS.

1 | Introduction

Synchronizing movements to sound is a natural response in humans. This behavior can be deliberate, as in dancing or clapping along music, or spontaneous, like when we tap our foot or nod our head without thinking during a concert. The beat is a basic characteristic of rhythm in music, and it underlies most pieces. Its temporal regularity makes it predictable. In turn, predictions enable us to coordinate movements to the perceived regularities, such as during speaking, walking, dancing, or playing a musical instrument. The ability to align movements to an auditory beat (auditory–motor synchronization, AMS) arises early in life [1, 2] and is widespread in the general population [3, 4]. Difficulties in AMS have been linked to neurodevelopmental [5–8] and neurodegenerative disorders [9, 10]. Interestingly, patients with motor disorders such as Parkinson's disease can benefit from rhythmic auditory cues (for reviews, see Refs. [11, 12]). Gait improvements such as reduced variability, increased speed, and increased stride length are well documented in these patients [13–16].

These effects of rhythm on movement may be possible due to the tight link between auditory and motor areas in the brain [17–19] (for a recent review, see Ref. [20]). When listening to an auditory beat (in the absence of movement), a broad neural network including auditory regions, motor regions, and sensorimotor integration areas is activated. It is no surprise that areas associated with audition such as the superior temporal gyrus are active during listening tasks. More surprisingly is the activation of the supplementary motor area, basal ganglia and cerebellum [17, 21–23], typically known for their role in motor control and action planning in the absence of external rhythmic stimulation

[24–26]. While the basal ganglia (e.g., the putamen) appears central in beat processing, areas like the supplementary motor area and the cerebellum are particularly active for perceiving complex rhythms [27]. Cortical and subcortical regions involved in beat perception are thus overlapping with those involved in action planning and production. A theory accounting for the tight link between perception and action is the Action Simulation for Auditory Prediction (ASAP) hypothesis, which postulates that the internal (unconscious) simulation of movements by motor areas enables precise temporal predictions of the upcoming stimulus [28, 29]. In turn, these predictive abilities improve auditory processing [30] and thus, beat perception, which is necessary for AMS [16, 31].

AMS can be modeled using different approaches. Computational models, such as the Wing and Kristofferson [32] model, distinguish two key components in rhythmic movement production: an internal clock underlying spontaneous movement rate, and a motor implementation process that introduces delays to produce the actual movement. During AMS, sensorimotor delays must be compensated to reach a synchronized state. Such compensation happens through implementation of phase and period adjustments [33, 34]. Another approach for understanding AMS derives from the dynamical system theory. In this framework, movements and auditory cues are modeled by two distinct oscillators, which both have their own preferred frequency. Spontaneous movement rate (e.g., uncued step cadence for walking) defines the preferred frequency of the movement oscillator, while the beat of the auditory stimulus constitutes the frequency of the other oscillator. The distance between the oscillators' frequencies defines the synchronization region where coupling (i.e., synchronization) is possible. For coupling to occur, the two frequencies must be sufficiently close [35, 36] or their ratio be close to an integer ratio [37]. The larger the synchronization region, the greater the coupling strength. If the stimulus' frequency is too far from the spontaneous motor frequency, however, synchronization may suffer [35]. An influential model of rhythm perception—the dynamic attending theory [38, 39]— builds on dynamical system theory. According to the dynamic attending theory, temporal predictions, which are critical for achieving AMS, derive from the coupling of internal neurocognitive oscillations [40–42] reflecting attending mechanisms to rhythmic auditory stimuli. Indeed, attention oscillates through time, and attentional energy is expected to be maximal whenever a sensory event is most likely to occur. For example, the metrical structure typically found in music leads to the perception of an underlying beat or pulse, while driving strong expectations for sensory events (e.g., notes, chords) to fall on the beat. When notes occur in-between beats, as is the case in syncopated rhythms, temporal expectations are violated [43] leading to prediction errors. In the predictive coding theory [44, 45], the brain aims to minimize prediction errors by adjusting internal models until predictions match sensory input. When we dance to syncopated rhythms, we typically move to the beat of music, thus minimizing prediction errors [44]. Together, these models highlight the interplay between intrinsic motor rhythms, external auditory cues, and attention, offering a comprehensive framework for understanding the mechanisms underlying AMS.

In sum, different theories can model the processes and brain mechanisms underlying AMS. In addition to these general mechanisms, a critical element to achieve AMS pertains to an individual's ability to track the beat and coordinate motor activity leading to synchronization.

2 | Rhythmic Abilities

Rhythmic abilities encompass beat perception, motor production, as well as sensorimotor integration. Beat perception is the ability to extract the beat from an auditory sequence without overt movement, while motor production refers to the production of rhythmic movements whether a pacing stimulus is present or not. Finally, sensorimotor integration is the process where stimulus timing is mapped onto action timing during planning, eventually leading to precise AMS. These abilities are tested with a variety of perceptual and production tasks, such as the beat alignment test (BAT) [46], and paced and unpaced finger tapping [36]. A very common model to test AMS and motor performance is finger tapping [36, 47]. Test batteries such as the Harvard Beat Alignment Test (H-BAT) [48] and the Battery for the Assessment of Auditory Sensorimotor and Timing Abilities (BAASTA) [4] have been devised to provide a systematic assessment of rhythmic abilities. For example, tasks taken from BAASTA are capable of characterizing individual differences in both musicians and nonmusicians. Notably, adult norms for BAASTA were published for the first time by Dalla Bella et al., providing a reference point for its application to clinical populations [4].

Studies in quite large cohorts generally reveal a link between rhythm perception (e.g., tested with the BAT) and AMS [49, 50]. These relationships point to a general rhythm system, supporting both perception and action—a view which is compatible with the ASAP theory [28, 29]. The idea of a general rhythm system is supported by clinical studies in patients with movement disorders [51]. In Parkinson's disease, movement velocity [52] and variability [53] show cross-effector correlations when performing rhythmic tasks such as tapping, walking, and speaking. Motor variability can further be predicted by patients' beat perception [53]. Finally, there is evidence that training AMS in this population can improve motor performance across different effectors, a benefit linked to improved beat perception [54]. In the context of rehabilitation, having a generalized rhythm system is of interest as patients can gain cross-effector benefits from training a single effector [54].

Although individuals with neurodevelopmental [5–8] and neurodegenerative disorders [9, 10, 55] show deficits in rhythmic abilities, they can also be selectively impaired in perception or production. In fact, some studies report a lack of relationship between beat perception and AMS in healthy and clinical populations [3, 4, 48, 56–59]. This suggests, that even though rhythm perception and production are tightly coupled, there may still be some degree of independence at the functional level, and that the underlying mechanisms may be dissociated in populations with disorders. Moreover, there is preliminary evidence in patients with Parkinson's disease that rhythmic training via finger tapping can transfer to verbal production (i.e., by reducing motor variability when repeating syllables in a loop as fast as possible), but not to walking, as interstep interval variability remains similar post intervention [54]. Thus, timing-control mechanisms may differ for tapping (a minimal motor task) and walking (a full-body task), raising the question of whether assessing motor production and sensorimotor integration with finger-tapping tasks suffices to gain a good understanding of one's rhythmic profile.

Notably, finger tapping as a model for testing AMS has many advantages. It is easy to implement both in laboratory and clinical settings as it requires minimal equipment, such as general MIDI instruments or off-the-shelf mobile devices [49, 60]. Tapping can also be tested in a brain-imaging scanner to investigate the neural correlates of rhythmic abilities [21]. At the same time, finger tapping presents several drawbacks. It is not an ecological task and may thus limit our understanding of AMS and its underlying mechanisms. Indeed, conclusions drawn from highly controlled tapping experiments may not transfer fully to everyday-life situations, like walking or speaking. For example, walking requires the coordination of multiple effectors and is mostly automatic, while tapping is primarily voluntary and engages only one effector with limited constraints. There are also no consequences in producing unequal finger taps, while unstable gait predicts falls [61]. Walking or speech articulation have clear functional roles, which are absent from tapping. Assessing finger tapping alone may thus not give a full picture of an individual's rhythmic profile.

The aim of this article is to propose gait as an alternative behavioral model for studying AMS. Walking is an inherently rhythmic behavior, as is visible in the regularity of the gait cycle, with high ecological validity. It is rooted in biology as an evolutionary trait, which was acquired over 4 million years ago by our ancestors, as a response to critical environmental pressures linked to changing habitat and a need for efficient harvest [62, 63]. Bipedalism was also paramount in the evolution of other human traits, like speech [64]. Moving from a quadrupedal to an upright position freed the thorax from its support role, leading to the formation of the modern vocal tract and uncoupling of breathing from locomotor functions, a necessity for speech production [64, 65]. Gait emerges spontaneously within the first year of life and follows a regular development in children. We usually can walk at age one, and reach a gait pattern similar to adults' by age seven [66]. Although walking is mostly automatic, it remains under voluntary control for initiation, termination, turning, and obstacle avoidance [67]. Unlike tapping, gait also has a clear functional role. Locomotion is subjected to environmental constraints and requires the coordination of all limbs for the body to stay upright. Loss of coordination may compromise balance, leading to falls and injuries [68]. Altogether, gait offers an evolutionarily grounded and functionally rich behavioral model that can capture the complexity and ecological validity necessary to study AMS.

3 | Walking as a Model of Auditory–Motor Synchronization

3.1 | Single-Effector Versus Whole-Body Movements

When walking to an auditory beat, the alignment of footfalls to the rhythmic stimulus is obviously more complex than for finger tapping, as gait requires whole-body movements and interlimb coordination. Accurately aligning steps to a pacing stimulus irrespective of the movements of other effectors would lead to an unnatural gait pattern. As such, gait analysis requires taking into account all parts of the lower limbs simultaneously [69, 70]. Analyses assessing effects of a pacing stimulus on gait often focus on spatiotemporal parameters (Figure 1) like gait velocity, cadence (i.e., number of steps per minute), stride length, and variability of interstep intervals and of stride lengths [71]. More rarely, lower-limb kinematics (e.g., joint angles) and kinetics (e.g., joint moments) are also assessed [72–74]. All of these gait parameters are very much affected by gait speed [75]. Speed is determined by cadence and stride length, which are most often targeted by rhythm interventions [76, 77]. Because deviating from gait preferred frequency will impact all effectors up the kinematic chain, the choice of pacing frequency should be carefully considered. Conversely, in tapping, changes in the finger's rate and/or trajectory should not affect other limbs. In sum, AMS during gait involves complex whole-body coordination unlike finger tapping, requiring a comprehensive analysis of spatiotemporal and biomechanical parameters.

The coordination of multiple effectors is likely to rely on timing-control mechanisms that differ from those needed to produce regular finger taps. Alternatively, evidence of a link between tapping and walking performance would suggest similar mechanisms, in favor of a generalized rhythm system. At the moment, there is conflicting evidence regarding the existence of such a link. Indeed, previous studies attempted to predict rhythm-induced gait changes, based on participants' rhythmic abilities assessed with finger tapping [10, 78]. In patients with Parkinson's disease, poor AMS during tapping predicts an increase in gait speed following a cued–gait intervention [10]. AMS however does not seem to predict motor variability during gait in a sample of Parkinson's patients and controls [78]. One could argue that these null relationships stem from the comparison of motor production measures (e.g., variability of interstep intervals) to AMS variables. However, intertap interval variability was not correlated to interstep interval variability after a 6-week rhythm intervention [54]. Interlimb coordination, which is absent from tapping but inherent to gait, could be the source of the discrepancy. Altogether, it is unlikely that tapping performance can fully predict gait adaptation to rhythmic auditory cues, although more research directly comparing the two is needed.

3.2 | Discrete Versus Continuous Movements

Discrete movements are defined by salient events interspersed by breaks [79]. During tapping, finger velocity reaches zero when finishing its downward trajectory and then changes direction before reaching zero again at the apex. On the other hand, walking is defined as continuous, as there are no breaks in the motion until the task is stopped. Timing-control mechanisms of discrete and continuous movements have been compared in the past using the dual-task paradigm [80, 81]. In the present review, we consider dual-task paradigms that involve performing a primary motor task together with a secondary task that can be motor [81], cognitive [80], or both (i.e., name digits presented two cycles ago in an N-back task) [82]. The performance of the secondary task interferes with the primary task by increasing cognitive load. Interestingly, interference is not the same when the primary task is discrete or continuous. For example, when asked to perform a simultaneous working memory task, cellists' variability increases for discrete (i.e., staccato), but not continuous (i.e., legato) upper-limb bowing movements [80]. Here, the cognitive task only

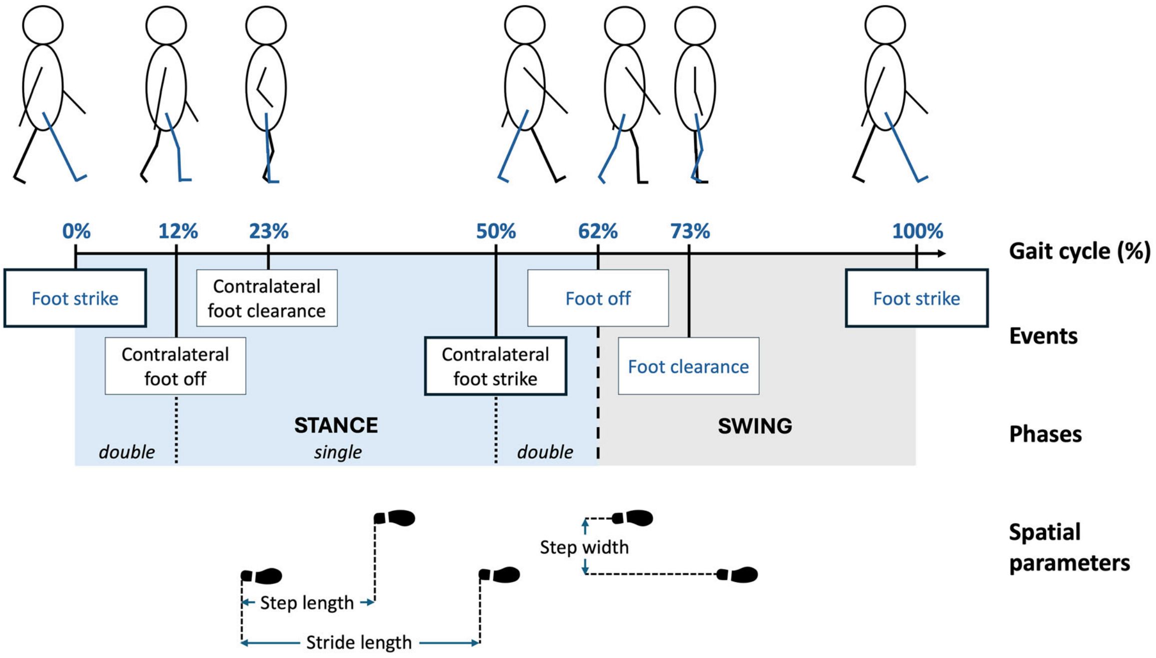

FIGURE 1 | The gait cycle expressed in percentages. Gait events, phases, and spatial parameters are expressed for the right leg (in blue).

interferes with the discrete, but not the continuous motor task. Similar results are observed while performing two competing motor tasks, namely, tapping and walking. Indeed, young healthy adults can maintain a 375-ms tapping rate independently of a 600-ms walking rate [81]. However, if stepping becomes a discrete task (i.e., unilateral or bilateral foot tapping), finger-tapping rate increases to reach a 2:1 ratio with stepping rate. Thus, a discrete task cannot be performed independently of another discrete motor task or a purely cognitive task. Overall, the results indicate that discrete movements require more cognitive resources than continuous ones.

It has been proposed that temporal regularity of discrete movements relies on a pacemaker (i.e., internal clock) [83]. According to clock models, pulses generated by the pacemaker are stored in working memory and compared to timing of discrete events [84]. Error correction thus happens for each repetition. On the other hand, continuous movements would rely on emergent timing, which arises from movement dynamics [85, 86]. At 2 Hz and above, flexion–extension of the finger becomes a continuous movement, as motion breaks are no longer observed in the finger trajectory [86]. This may explain the tendency to speed up discrete actions during simultaneous performance of a cognitive task [80, 82]. By increasing movement rate, action timing may become more dynamically driven, freeing up cognitive resources. These resources can then be allocated to the cognitive task in a dual-task paradigm.

This speeding-up advantage goes against the view of dynamical systems theory, which predicts a loss of stability at increased tempi [87]. Torre and Balasubramaniam [88] proposed that clock models, such as the Wing and Kristofferson [32] model, and dynamical systems could explain the differences observed between discrete and continuous movements during AMS, respectively. Negative lag 1 autocorrelations (i.e., shortened intervals are followed by lengthened ones and vice versa) measured when finger tapping on a surface show that error correction happens on each repetition, while the lack of negative lag 1 autocorrelations for continuous movements imply that action timing is adjusted continuously as proposed by dynamical systems [89].

Intuitively, we would expect the simultaneous performance of two continuous movements to be unchallenging, if timing can be dynamically driven. In two studies [90, 91], Sakamoto et al. showed that leg cycling rate affected arm cycling rate but that arm cycling rate did not impact leg cycling rate. These studies suggest that there could be a difference between upper- and lower-limb rhythmic motion, despite both movements being continuous. Similar observations are made when looking at AMS. Participants are better at matching metronome tempo during foot stepping than hand circle drawing, despite foot stepping being a discrete motion [92]. Further, synchronization can be maintained when stepping in place regardless of tempo, while synchronization during circle-drawing is negatively impacted by faster pacing stimuli. Despite these results, it is unlikely that differences between upper- and lower-limb rhythmic motion are effector driven. Indeed, we mentioned previously that rhythmic tapping with the finger could only be maintained while walking, but not foot tapping. This discrepancy could be due to the discrete nature of foot tapping, but also to gait automaticity. In sum, different timing-control mechanisms are at play when performing discrete and continuous movements. These differences are likely to be relevant when assessing AMS.

3.3 | Voluntary Versus Automatic Movements

One could argue that highly trained musicians are experts at finger tapping, which resembles piano keystrokes and left-hand motion of guitar and other string players. Indeed, instrumentalists often perform better on rhythm production tasks than nonmusicians [4, 93–96]. For example, Tranchant et al. [97].

reported intertap intervals with ∼5% variability in musicians and with ∼6% variability in nonmusicians, similar to values reported in BAASTA norms [49]. As for walking, most of us become experts during childhood [66]. Interestingly, and in spite of walking being a more complex multilimb task than tapping, variability of interstep intervals during gait for young [31] and older individuals [98] is twice lower than values of intertap interval variability in musicians [49, 97]. The level of stability achieved during gait may be due to its automaticity.

Gait automaticity is possible owing to its reliance on specific neural structures. Gait recruits both spinal and supraspinal neural networks [99]. The automatic component of gait is implemented by central pattern generators located in the inferior part of the spinal cord, which ensure repetitiveness of the gait cycle and alternating left–right movements at a regular pace when further monitoring is not needed [100–102]. Gait being autonomous, stable, and inherently rhythmic, it is often modeled as an inverted pendulum [103], which makes it an ideal behavior to be studied under the lens of dynamical systems [104]. As an oscillator, gait has an intrinsic frequency with little interindividual variability [105] compared to tapping [106]. As predicted by dynamical systems [107], coupling to an external oscillator (e.g., rhythmic auditory cues) during gait is possible if the external frequency is close enough to spontaneous cadence [35]. Importantly, the level of automaticity achieved through central pattern generators explains why we can walk while successfully performing other tasks [81]. On the other hand, voluntary control is afforded by cortical and subcortical structures receiving feedback from central pattern generators and whose functions allow us to initiate, stop, and change directions, making gait flexible and adaptable to varying environmental demands [99, 100, 108, 109]. Notably, finger or foot tapping lack the aforementioned automatic component. As a result, cognitive resources must be shared when these actions are performed together with a secondary task [82], leading to greater interference than in a walking task [81].

Overall, the studies reviewed in this section suggest a dissociation between tapping, which relies mostly on supraspinal structures, and walking, which is both automatic and voluntary due to the involvement of central pattern generators and cortical and subcortical structures, respectively. As it is possible to manipulate the degree of automaticity required to complete a gait task (e.g., walking on a pressure mat in a lab vs. around a university campus), gait offers the possibility of studying both voluntary and automatic components during AMS.

In conclusion, while AMS can be assessed through both tapping and walking, these tasks differ fundamentally in movement complexity (i.e., fine vs. gross movements), timing-control, and neural mechanisms. The choice of the appropriate target movement can be driven by the research question, while considering the aforementioned differences when designing an experimental protocol. For example, tapping may be more suited to answer questions related to aspects of AMS and timing that can be isolated from whole-body coordination, when minimal motor involvement is needed, or when the focus is primarily on voluntary motor control. There are also pragmatic reasons for choosing tapping over gait. Indeed, walking tasks may be overly challenging for certain individuals, like stroke patients, making tapping a great alternative to assess rhythmic abilities. Alternatively, gait offers the unique opportunity to study both automatic and voluntary components of motor control. This might be particularly relevant when working with Parkinson's disease patients as walking progressively switches from automatic to attentional control as the disease progresses [110]. Even though testing AMS using gait is certainly more demanding than asking participants to perform a tapping task, gait has the advantage of having high ecological validity and is likely more scalable to everyday life. In the context of rehabilitation, gait tasks can inform on functional deficits linked to autonomy and well-being that cannot be addressed with tapping. Figure 2 summarizes the differences between tapping and walking, which are critical in the design of AMS protocols.

4 | Training Rhythmic Abilities

The links we previously described between beat perception and AMS support the concept of a general rhythm system. This hypothesis suggests that motor benefits for a given effector should increase following training that is focused on another effector (i.e., near transfer) or even nonmotor training (i.e., far transfer). This prospect is particularly relevant for rehabilitating patients with movement disorders who may experience cross-effector benefits from training rhythmic abilities [54]. Beyond movement, rhythmic abilities and music training have been linked to executive functions in healthy individuals [111–113], neurodevelopmental [5–7, 114], and neurodegenerative disorders [115]. For example, children and adults with attention deficit/hyperactivity disorder (ADHD) with greater beat perception and AMS abilities display better performance in cognitive flexibility and inhibition tests compared to those with poorer rhythmic abilities [5]. Cognitive flexibility refers to the ability to adapt behavior to changing task rules [116]. Inhibition involves controlling attention to suppress or delay dominant responses, while working memory refers to the ability to retain and manipulate information [116]. Notably, inhibition control and working memory—both positively correlated with motor production and sensorimotor integration [111, 117]—are crucial aspects of executive functioning. Overall, there is evidence that rhythmic abilities are associated with enhanced cognitive functions. Therefore, training rhythmic abilities may positively influence cognitive performance, which could be particularly beneficial for slowing the cognitive decline associated with normal aging or for supporting individuals with neurological disorders linked to cognitive deficits. In the following section, we first review interventions specifically targeting rhythmic abilities, and then present a discussion of how motor training can enhance both motor and nonmotor skills.

4.1 | Rhythm-Specific Training

Several forms of interventions exist to train rhythmic abilities. The most general form of training is learning to play a musical instrument, which typically includes training rhythmic abilities among other skills. Musicians often outperform nonmusicians on rhythmic tasks [93, 94]. Interestingly, instrumental music training shows transfer effects that go beyond music, probably due to brain-related changes associated with music practice [118]. Although there is currently a debate in the literature regarding the effect of music training on cognitive functions in children [119], growing evidence is in favor of musical interventions, more so than other types of artistic or academic pursuits and sports

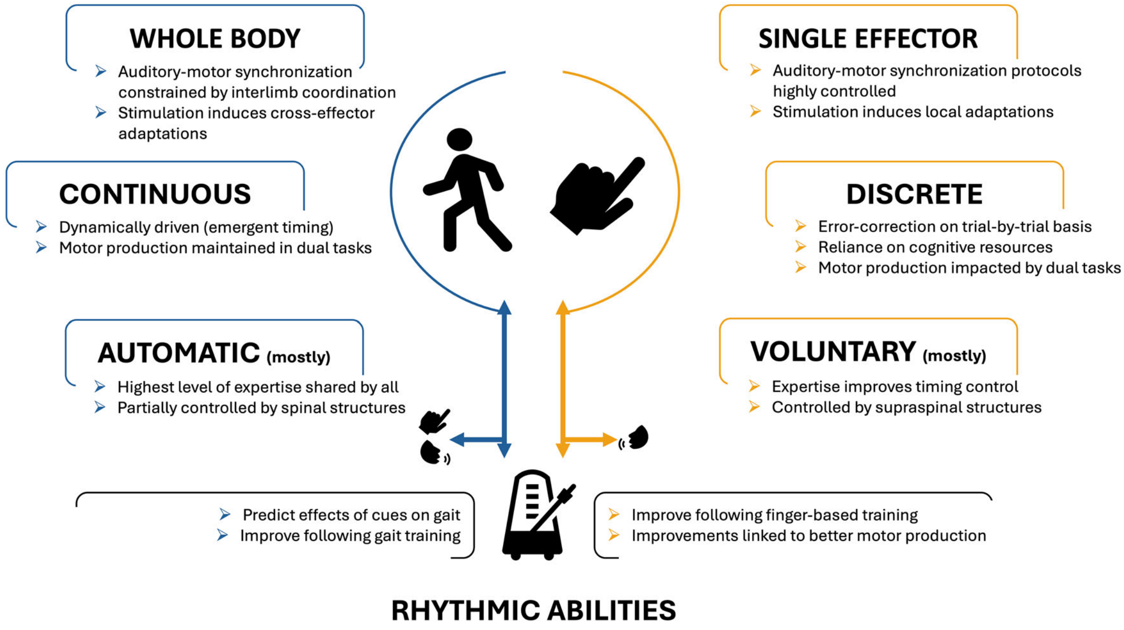

FIGURE 2 | Walking as a model of auditory–motor synchronization compared to finger tapping. Reciprocal arrows indicate effects of rhythmic abilities on motor production and sensorimotor integration, as well as positive impact of gait and finger-based training on rhythmic abilities.

[117, 120–122]. For example, beneficial effects of music training have been shown in inhibition [117] and working memory [120]. Similar results are also observed in older individuals following music training [123–125]. Music interventions are particularly promising for rehabilitation because they are both pleasurable and rewarding [126]. One particularly interesting form of musical activity is drumming. Drumming seems to fall somewhere in-between finger tapping and walking as it can involve all four limbs (on a drum set), requires bilateral coordination, and specifically engages the rhythmic component of music training. Drummers have been shown to outperform other musicians in rhythmic tasks [127], although these differences may be limited to more difficult tasks (i.e., synchronizing to a triple meter) [128]. Notably, drummers often must perform two rhythms independently. They may thus be better at maintaining rhythmic movements [129] while having to perform a secondary task, although motor control remains voluntary during music practice, likely relying on similar neural structures as tapping. Drumming therefore may offer an alternative model for investigating rhythmic abilities and their neural mechanisms, while also opening promising avenues for interventions aimed at enhancing motor coordination and dual-task performance. However, and in spite of all the benefits linked with music practice, music lessons are not always accessible due to barriers such as cost, limited availability of instructors, and transportation requirements. In addition, music practice trains more than just rhythmic abilities, making it difficult to isolate effects of improved rhythmic skills. Therefore, it is essential to explore alternative approaches to training rhythmic abilities that may be more accessible and specifically target rhythmic skills, such as cued–gait training (see Section 4.2) and serious games.

Serious games—designed with goals beyond mere entertainment—can be used for motor rehabilitation in various patient populations (e.g., stroke, Parkinson's disease, cerebral palsy, etc.) [130], as well as to devise training targeted at rhythmic abilities [131]. These interventions are particularly appealing because they are affordable, accessible, and can be performed at home with minimal involvement from medical professionals. They may be a suitable alternative for patients with motor disorders for whom learning to play a musical instrument may be too challenging. One example of a serious game designed to enhance rhythmic abilities is *Rhythm Workers* [131], a tablet-based game where users must tap in time with music to construct buildings. After a 6-week training period, individuals with Parkinson's disease demonstrate improved beat perception compared to those playing a control game [54]. Enhanced beat perception is also linked to improvements in motor production during both manual tasks (i.e., tapping) and verbal tasks (i.e., articulating syllables as fast as possible), suggesting that training rhythmic abilities can transfer to different effectors, regardless of whether they were specifically targeted during training. More recently, this approach was applied to training rhythmic abilities in children with neurodevelopmental disorders. In a pilot study, we found that a 2-week training is effective in improving rhythmic abilities in children with ADHD, relative to an active control condition [114]. Notably, we found first evidence of an improvement of inhibition and flexibility in this clinical population [114]. Although serious games offer a promising approach to enhancing beat perception and motor production, transfer to other effectors is partial, as interstep interval variability did not decrease post intervention [54]. Interestingly, playing *Rhythm Workers* did prevent the increase in interstep interval variability seen in the active control group [54]. Nonetheless, this limited transfer effect may be due to differences in the timing mechanisms employed by various types of movements, as described in the previous section.

4.2 | Gait Training

Another way to implement rhythmic training involves having patients walk with rhythmic cues, such as metronome tones or music clips, in a rehabilitation program lasting several weeks [132, 133] (for reviews, see Refs. [134, 135]). Locomotion is essential for autonomy and, consequently, for quality of life and well-being [136]. Gait rehabilitation offers the advantage of fostering a functional gain leading to increased independence, while keeping patients physically active during the training itself. Having patients walk on a regular basis over several weeks has been shown to produce positive changes in gait and balance post intervention, even in the absence of cues [137, 138]. The rewarding nature of music [126] makes cued–gait training particularly appealing for motor rehabilitation. Rhythmic auditory cues can induce immediate improvements during walking in Parkinson's disease [16, 76, 139, 140], cerebral palsy [77], and stroke [141], for example. When performed over 3–24 weeks, cued–gait training not only improves gait spatiotemporal parameters immediately post intervention [142–144], but also sometimes after the intervention has ceased [145, 146], though reports are inconsistent [147]. Interestingly, rhythm interventions also enhance rhythmic abilities, namely, beat perception and AMS [10, 148].

Gait has both automatic and voluntary components. Timing involved with voluntary action (e.g., gait initiation, stopping, and turning) can thus transfer to tapping performance and other voluntary motor commands. In contrast, motor gains from rehabilitation designed to focus exclusively on finger movements, such as serious games, may not transfer to full-body, continuous, and automatic movements [54]. Cued–gait rehabilitation may thus train rhythmic abilities more broadly than finger-tapping-based interventions.

One way to implement cued–gait training is by using technologies that adapt stimulus-presentation rate to individual cadences. These technologies have shown positive effects on gait (e.g., speed increase) in neurotypical and patient populations [149–151]. Such technologies can provide metronome cues that match individuals' preferred cadence in order to facilitate gait, but can also provide gradual tempo changes, which could be harnessed to train beat perception, AMS and gait itself in an enjoyable fashion. Cochen De Cock et al. tested effects of such intervention on Parkinson's disease patients with BeatMove, which provides musical stimuli synchronized to participants footsteps with gradual tempo changes to elicit faster cadence. After a 4-week intervention, patients improved not only spatial and temporal gait parameters, but also overall physical activity and reported satisfaction with the device [152]. These results are very promising for the design of personalized gait interventions for patients with movement disorders.

In sum, training rhythmic abilities can lead to benefits in motor and cognitive performance. Cued–gait interventions may be ideal to train rhythmic skills more broadly, as gait has both automatic and voluntary components that can transfer to other movements. Gait also has the advantage of being functional, since it facilitates autonomy and keeps patients physically active. Combining music cues with gait training will make interventions more enjoyable and rewarding. Alternatively, music lessons and specifically drum lessons, may lead to similar benefits. Future studies comparing near- and far-transfer effects following cued–gait, serious games and drum interventions are needed.

5 | Practical Implications and Challenges for Testing Gait

Assessing AMS using gait may seem challenging without access to expensive motion capture systems or instrumented treadmills, typically found in biomechanics laboratories. Additionally, using brain-imaging techniques during gait, such as electroencephalography (EEG) or functional near-infrared spectroscopy (fNIRS), may seem arduous due to their sensitivity to motion artifacts. In this section, we offer practical ways to implement gait paradigms using equipment that can be found in music cognition laboratories and protocols that can be easily devised with sets of sensors and microcontrollers (e.g., Arduino-based).

Data collection in tapping experiments often relies on force signals from force sensitive resistors (FSRs) to extract tap events. An example is the TeensyTap device [153], in which an FSR is connected to a teensy microcontroller board (PJRC, Portland, Oregon, USA), coupled to an audio extension shield to record tap data while providing auditory stimulation. Our team recently adapted this technology to gait with TeensyStep [150], offering a cheap and portable alternative to construct flexible AMS paradigms during locomotion while keeping high level temporal precision. Codes for TeensyTap (https://github.com/florisvanvugt/teensytap) and TeensyStep (https://github.com/dallabella-lab/teensystep) are open source and can be easily adapted to a researcher's interests. Using FSRs rather than motion capture systems or instrumented force plates also facilitates the transfer of AMS protocols to both ecological (i.e., outside the lab) and clinical settings, as equipping patients with reflective markers or a harness may be suboptimal.

Studying gait at the neural level requires portable devices such as EEG and fNIRS. One drawback of these devices is their sensitivity to motion artifacts inherent to walking tasks [154–156]. Nonetheless, multiple algorithms have now been developed to improve signal-to-noise ratio [154], such as the BeMoBIL pipeline [157], leading to an increasing number of gait publications in the last two decades [158–160].

Together, these cost-effective and accessible hardware and software developments pave the way for assessment of gait and its neural underpinnings in the context of AMS research.

6 | Conclusion and Perspectives

Finger tapping has significantly contributed to our understanding of AMS due to its simplicity and ease of use in both the laboratory and at home. It serves as a reliable proxy for assessing AMS in research and clinical settings when time and equipment is limited. However, finger tapping is a single effector, discrete, and mostly voluntary movement which timing heavily relies on cognitive resources and structures. Tapping is a relatively unstable motor behavior that is difficult to sustain while simultaneously performing other cognitive or motor tasks. Consequently, assessing motor production and AMS using only the finger may provide an incomplete picture of one's rhythmic profile. Moreover, findings from finger-tapping tasks may not translate well to other types of movements such as walking.

Despite the greater difficulty in testing and measuring gait performance, walking offers a more comprehensive perspective on rhythmic abilities. It involves the coordination of multiple effectors, is continuous, and is largely automatic. Gait training can improve all dimensions of rhythmic abilities, including beat perception, motor production, and sensorimotor integration. Additionally, recent technological advancements such as Mobile Brain/Body Imaging (MoBI) [161] have made it possible to investigate more naturalistic movements, like walking, even at the cortical level. This progress allows researchers to move beyond highly controlled environments to study rhythmic abilities through truly rhythmic motor actions.

Studies are now needed to directly compare finger tapping and walking across various paradigms (e.g., spontaneous movements, synchronization, dual tasking) to better understand differences in timing-control mechanisms. Comparing different types of interventions across diverse populations will also be essential for refining the concept of a generalized rhythm system and developing patient-specific rehabilitation protocols.

Author Contributions

Both authors discussed and agreed on the conception of the manuscript and its main topics. They both contributed to the writing and approved the final version for publication.

Acknowledgments

This research was supported by the Fonds de recherche du Québec—Nature et technologies (FRQNT) doctoral training scholarship, awarded to Clara Ziane; as well as by a Discovery Grant (RGPIN-2019-05453) from the Natural Sciences and Engineering Research Council of Canada (NSERC) and the Canada Research Chair program (CRC in Music Auditory-Motor Skill Learning and New Technologies), awarded to Simone Dalla Bella.

Conflicts of Interest

The authors declare no conflicts of interest.

References

1. S. Kirschner and M. Tomasello, "Joint Drumming: Social Context Facilitates Synchronization in Preschool Children," *Journal of Experimental Child Psychology* 102, no. 3 (2009): 299–314, https://doi.org/10.1016/j.jecp.2008.07.005.

2. S. Fujii, H. Watanabe, H. Oohashi, M. Hirashima, D. Nozaki, and G. Taga, "Precursors of Dancing and Singing to Music in Three-to Four-Months-Old Infants," *PLoS ONE* 9, no. 5 (2014): e97680, https://doi.org/10.1371/journal.pone.0097680.

3. J. Sowiński and S. Dalla Bella, "Poor Synchronization to the Beat May Result From Deficient Auditory-Motor Mapping," *Neuropsychologia* 51, no. 10 (2013): 1952–1963, https://doi.org/10.1016/j.neuropsychologia.2013.06.027.

4. S. Dalla Bella, S. Janaqi, C.-E. Benoit, et al., "Unravelling Individual Rhythmic Abilities Using Machine Learning," *Scientific Reports* 14, no. 1 (2024): 1135, https://doi.org/10.1038/s41598-024-51257-7.

5. F. Puyjarinet, V. Bégel, R. Lopez, D. Dellacherie, and S. Dalla Bella, "Children and Adults With Attention-Deficit/Hyperactivity Disorder Cannot Move to the Beat," *Scientific Reports* 7, no. 1 (2017): 11550, https://doi.org/10.1038/s41598-017-11295-w.

6. V. Noreika, C. M. Falter, and K. Rubia, "Timing Deficits in Attention-Deficit/Hyperactivity Disorder (ADHD): Evidence From Neurocognitive and Neuroimaging Studies," *Neuropsychologia* 51, no. 2 (2013): 235–266, https://doi.org/10.1016/j.neuropsychologia.2012.09.036.

7. V. Bégel, S. Dalla Bella, Q. Devignes, M. Vandenbergue, M.-P. Lemaître, and D. Dellacherie, "Rhythm as an Independent Determinant of Developmental Dyslexia," *Developmental Psychology* 58, no. 2 (2022): 339, https://psycnet.apa.org/doi/10.1037/dev0001293.

8. M. J. Hove, N. Gravel, R. M. Spencer, and E. M. Valera, "Finger Tapping and Pre-Attentive Sensorimotor Timing in Adults With ADHD," *Experimental Brain Research* 235 (2017): 3663–3672, https://doi.org/10.1007/s00221-017-5089-y.

9. J. A. Grahn and M. Brett, "Impairment of Beat-Based Rhythm Discrimination in Parkinson's Disease," *Cortex; A Journal Devoted to the Study of the Nervous System and Behavior* 45, no. 1 (2009): 54–61, https://doi.org/10.1016/j.cortex.2008.01.005.

10. S. Dalla Bella, C.-E. Benoit, N. Farrugia, et al., "Gait Improvement via Rhythmic Stimulation in Parkinson's Disease Is Linked to Rhythmic Skills," *Scientific Reports* 7, no. 1 (2017): 1–11.

11. C. Nombela, L. E. Hughes, A. M. Owen, and J. A. Grahn, "Into the Groove: Can Rhythm Influence Parkinson's Disease?," *Neuroscience & Biobehavioral Reviews* 37, no. 10 (2013): 2564–2570, https://doi.org/10.1016/j.neubiorev.2013.08.003.

12. S. J. Spaulding, B. Barber, M. Colby, B. Cormack, T. Mick, and M. E. Jenkins, "Cueing and Gait Improvement Among People With Parkinson's Disease: A Meta-Analysis," *Archives of Physical Medicine and Rehabilitation* 94, no. 3 (2013): 562–570, https://doi.org/10.1016/j.apmr.2012.10.026.

13. G. C. McIntosh, S. H. Brown, R. R. Rice, and M. H. Thaut, "Rhythmic Auditory-Motor Facilitation of Gait Patterns in Patients With Parkinson's Disease," *Journal of Neurology, Neurosurgery & Psychiatry* 62, no. 1 (1997): 22–26, https://doi.org/10.1136/jnnp.62.1.22.

14. P. Arias and J. Cudeiro, "Effects of Rhythmic Sensory Stimulation (Auditory, Visual) on Gait in Parkinson's Disease Patients," *Experimental Brain Research* 186 (2008): 589–601, https://doi.org/10.1007/s00221-007-1263-y.

15. R. A. Miller, M. H. Thaut, G. C. McIntosh, and R. R. Rice, "Components of EMG Symmetry and Variability in Parkinsonian and Healthy Elderly Gait," *Electroencephalography and Clinical Neurophysiology/Electromyography and Motor Control* 101, no. 1 (1996): 1–7, https://doi.org/10.1016/0013-4694(95)00209-X.

16. S. Dalla Bella, D. Dotov, B. Bardy, and V. Cochen De Cock, "Individualization of Music-Based Rhythmic Auditory Cueing in Parkinson's Disease," *Annals of the New York Academy of Sciences* 1423, no. 1 (2018): 308–317, https://doi.org/10.1111/nyas.13859.

17. J. L. Chen, V. B. Penhune, and R. J. Zatorre, "Listening to Musical Rhythms Recruits Motor Regions of the Brain," *Cerebral Cortex* 18, no. 12 (2008): 2844–2854, https://doi.org/10.1093/cercor/bhn042.

18. J. L. Chen, R. J. Zatorre, and V. B. Penhune, "Interactions Between Auditory and Dorsal Premotor Cortex During Synchronization to Musical Rhythms," *Neuroimage* 32, no. 4 (2006): 1771–1781, https://doi.org/10.1016/j.neuroimage.2006.04.207.

19. J. L. Chen, V. B. Penhune, and R. J. Zatorre, "Moving on Time: Brain Network for Auditory-Motor Synchronization Is Modulated by Rhythm Complexity and Musical Training," *Journal of Cognitive Neuroscience* 20, no. 2 (2008): 226–239, https://doi.org/10.1162/jocn.2008.20018.

20. M. Pranjić, T. B. Janzen, N. Vukšić, and M. Thaut, "From Sound to Movement: Mapping the Neural Mechanisms of Auditory–Motor Entrainment and Synchronization," *Brain Sciences* 14, no. 11 (2024): 1063, https://doi.org/10.3390/brainsci14111063.

21. L. A. Chauvigné, K. M. Gitau, and S. Brown, "The Neural Basis of Audiomotor Entrainment: An ALE Meta-Analysis," *Frontiers in Human Neuroscience* 8 (2014): 776, https://doi.org/10.3389/fnhum.2014.00776.

22. R. J. Zatorre, J. L. Chen, and V. B. Penhune, "When the Brain Plays Music: Auditory–Motor Interactions in Music Perception and Production," *Nature Reviews Neuroscience* 8, no. 7 (2007): 547–558, https://doi.org/10.1038/nrn2152.

23. J. A. Grahn and M. Brett, "Rhythm and Beat Perception in Motor Areas of the Brain," *Journal of Cognitive Neuroscience* 19, no. 5 (2007): 893–906, https://doi.org/10.1162/jocn.2007.19.5.893.

24. G. H. Yue, J. Z. Liu, V. Siemionow, V. K. Ranganathan, T. C. Ng, and V. Sahgal, "Brain Activation During Human Finger Extension and Flexion Movements," *Brain Research* 856, no. 1–2 (2000): 291–300, https://doi.org/10.1016/S0006-8993(99)02385-9.

25. M. G. Paulin, "The Role of the Cerebellum in Motor Control and Perception," *Brain, Behavior and Evolution* 41, no. 1 (1993): 39–50, 10.1159/000113822.

26. H. J. Groenewegen, "The Basal Ganglia and Motor Control," *Neural Plasticity* 10, no. 1–2 (2003): 107–120, https://doi.org/10.1155/NP.2003.107.

27. A. V. Kasdan, A. N. Burgess, F. Pizzagalli, et al., "Identifying a Brain Network for Musical Rhythm: A Functional Neuroimaging Meta-Analysis and Systematic Review," *Neuroscience & Biobehavioral Reviews* 136 (2022): 104588, https://doi.org/10.1016/j.neubiorev.2022.104588.

28. A. D. Patel and J. R. Iversen, "The Evolutionary Neuroscience of Musical Beat Perception: The Action Simulation for Auditory Prediction (ASAP) Hypothesis," *Frontiers in Systems Neuroscience* 8 (2014): 57, https://doi.org/10.3389/fnsys.2014.00057.

29. J. J. Cannon and A. D. Patel, "How Beat Perception Co-Opts Motor Neurophysiology," *Trends in Cognitive Sciences* 25, no. 2 (2021): 137–150, https://doi.org/10.1016/j.tics.2020.11.002.

30. B. Morillon, C. E. Schroeder, V. Wyart, and L. H. Arnal, "Temporal Prediction in Lieu of Periodic Stimulation," *Journal of Neuroscience* 36, no. 8 (2016): 2342–2347, https://doi.org/10.1523/JNEUROSCI.0836-15.2016.

31. L.-A. Leow, T. Parrott, and J. A. Grahn, "Individual Differences in Beat Perception Affect Gait Responses to Low- and High-Groove Music," *Frontiers in Human Neuroscience* 8 (2014): 811.

32. A. M. Wing and A. B. Kristofferson, "Response Delays and the Timing of Discrete Motor Responses," *Perception & Psychophysics* 14, no. 1 (1973): 5–12, https://doi.org/10.3758/BF03198607.

33. B. H. Repp and P. E. Keller, "Adaptation to Tempo Changes in Sensorimotor Synchronization: Effects of Intention, Attention, and Awareness," *Quarterly Journal of Experimental Psychology Section A* 57, no. 3 (2004): 499–521, https://doi.org/10.1080/02724980343000369.

34. J. Mates, "A Model of Synchronization of Motor Acts to a Stimulus Sequence: I. Timing and Error Corrections," *Biological Cybernetics* 70, no. 5 (1994): 463–473, https://doi.org/10.1007/BF00203239.

35. M. Roerdink, P. J. Bank, C. L. E. Peper, and P. J. Beek, "Walking to the Beat of Different Drums: Practical Implications for the Use of Acoustic Rhythms in Gait Rehabilitation," *Gait & Posture* 33, no. 4 (2011): 690–694, https://doi.org/10.1016/j.gaitpost.2011.03.001.

36. B. H. Repp, "Sensorimotor Synchronization: A Review of the Tapping Literature," *Psychonomic Bulletin & Review* 12, no. 6 (2005): 969–992.

37. E. E. Harding, J. C. Kim, A. P. Demos, et al., "Musical Neurodynamics," *Nature Reviews Neuroscience* 26, no. 5 (2025): 293–307, https://doi.org/10.1038/s41583-025-00915-4.

38. M. R. Jones and M. Boltz, "Dynamic Attending and Responses to Time," *Psychological Review* 96, no. 3 (1989): 459, https://doi.org/10.1037/0033-295X.96.3.459.

39. E. W. Large and M. R. Jones, "The Dynamics of Attending: How People Track Time-Varying Events," *Psychological Review* 106, no. 1 (1999): 119, https://doi.org/10.1037/0033-295X.96.3.459.

40. S. Nozaradan, I. Peretz, M. Missal, and A. Mouraux, "Tagging the Neuronal Entrainment to Beat and Meter," *Journal of Neuroscience* 31, no. 28 (2011): 10234–10240.

41. S. Nozaradan, I. Peretz, and P. E. Keller, "Individual Differences in Rhythmic Cortical Entrainment Correlate With Predictive Behavior in Sensorimotor Synchronization," *Scientific Reports* 6, no. 1 (2016): 1–12, https://doi.org/10.1038/srep20612.

42. T. Fujioka, L. J. Trainor, E. W. Large, and B. Ross, "Internalized Timing of Isochronous Sounds Is Represented in Neuromagnetic Beta Oscillations," *Journal of Neuroscience* 32, no. 5 (2012): 1791–1802, https://doi.org/10.1523/JNEUROSCI.4107-11.2012.

43. C. Song, A. J. Simpson, C. A. Harte, M. T. Pearce, and M. B. Sandler, "Syncopation and the Score," *PLoS ONE* 8, no. 9 (2013): e74692, https://doi.org/10.1371/journal.pone.0074692.

44. P. Vuust and M. A. Witek, "Rhythmic Complexity and Predictive Coding: A Novel Approach to Modeling Rhythm and Meter Perception in Music," *Frontiers in Psychology* 5 (2014): 1111, https://doi.org/10.3389/fpsyg.2014.01111.

45. P. Vuust, O. A. Heggli, K. J. Friston, and M. L. Kringelbach, "Music in the Brain," *Nature Reviews Neuroscience* 23, no. 5 (2022): 287–305, https://doi.org/10.1038/s41583-022-00578-5.

46. J. R. Iversen and A. D. Patel, "The Beat Alignment Test (BAT): Surveying Beat Processing Abilities in the General Population," paper presented at the 10th International Conference on Music Perception and Cognition, Sapporo, Japan, 2008.

47. B. H. Repp and Y.-H. Su, "Sensorimotor Synchronization: A Review of Recent Research (2006–2012)," *Psychonomic Bulletin & Review* 20 (2013): 403–452, https://doi.org/10.3758/s13423-012-0371-2.

48. S. Fujii and G. Schlaug, "The Harvard Beat Assessment Test (H-BAT): A Battery for Assessing Beat Perception and Production and Their Dissociation," *Frontiers in Human Neuroscience* 7 (2013): 771, https://doi.org/10.3389/fnhum.2013.00771.

49. S. Dalla Bella, N. E. Foster, H. Laflamme, et al., "Mobile Version of the Battery for the Assessment of Auditory Sensorimotor and Timing Abilities (BAASTA): Implementation and Adult Norms," *Behavior Research Methods* 56, no. 4 (2024): 3737–3756, https://doi.org/10.3758/s13428-024-02363-x.

50. P. Tranchant, M.-E. Lagrois, A. Bellemare, B. G. Schultz, and I. Peretz, "Co-Occurrence of Deficits in Beat Perception and Synchronization Supports Implication of Motor System in Beat Perception," *Music & Science* 4 (2021): 2059204321991713, https://doi.org/10.1177/2059204321991713.

51. C. M. Tolleson, D. G. Dobolyi, O. C. Roman, et al., "Dysrhythmia of Timed Movements in Parkinson's Disease and Freezing of Gait," *Brain Research* 1624 (2015): 222–231, https://doi.org/10.1016/j.brainres.2015.07.041.

52. S. Cantiniaux, M. Vaugoyeau, D. Robert, et al., "Comparative Analysis of Gait and Speech in Parkinson's Disease: Hypokinetic or Dysrhythmic Disorders?," *Journal of Neurology, Neurosurgery & Psychiatry* 81, no. 2 (2010): 177–184, https://doi.org/10.1136/jnnp.2009.174375.

53. F. Puyjarinet, V. Bégel, C. Gény, et al., "Heightened Orofacial, Manual, and Gait Variability in Parkinson's Disease Results From a General Rhythmic Impairment," *NPJ Parkinson's Disease* 5, no. 1 (2019): 19, https://doi.org/10.1038/s41531-019-0092-6.

54. F. Puyjarinet, V. Bégel, C. Geny, et al., "At-Home Training with a Rhythmic Video Game for Improving Orofacial, Manual, and Gait Abilities in Parkinson's Disease: A Pilot Study," *Frontiers in Neuroscience* 16 (2022): 874032, https://doi.org/10.3389/fnins.2022.874032.

55. A. Von Schnehen, L. Hobeika, M. Houot, et al., "Sensorimotor Impairment in Aging and Neurocognitive Disorders: Beat Synchronization and Adaptation to Tempo Changes," *Journal of Alzheimer's Disease* 100, no. 3 (2024): 945–959, https://doi.org/10.3233/JAD-231433.

56. V. Bégel, C.-E. Benoit, A. Correa, D. Cutanda, S. A. Kotz, and S. Dalla Bella, "Lost in Time but Still Moving to the Beat," *Neuropsychologia* 94 (2017): 129–138, https://doi.org/10.1016/j.neuropsychologia.2016.11.022.

57. M. D. Lense, E. Ladányi, T.-C. Rabinowitch, L. Trainor, and R. Gordon, "Rhythm and Timing as Vulnerabilities in Neurodevelopmental Disorders," *Philosophical Transactions of the Royal Society B* 376, no. 1835 (2021): 20200327, https://doi.org/10.1098/rstb.2020.0327.

58. P. Hsu, E. A. Ready, and J. A. Grahn, "The Effects of Parkinson's Disease, Music Training, and Dance Training on Beat Perception and Production Abilities," *PLoS ONE* 17, no. 3 (2022): e0264587, https://doi.org/10.1371/journal.pone.0264587.

59. K. K. Patterson, J. S. Wong, S. Knorr, and J. A. Grahn, "Rhythm Perception and Production Abilities and Their Relationship to Gait After Stroke," *Archives of Physical Medicine and Rehabilitation* 99, no. 5 (2018): 945–951, https://doi.org/10.1016/j.apmr.2018.01.009.

60. T. P. Zanto, N. T. Padgaonkar, A. Nourishad, and A. Gazzaley, "A Tablet-Based Assessment of Rhythmic Ability," *Frontiers in Psychology* 10 (2019): 2471.

61. M.-S. Kwon, Y.-R. Kwon, Y.-S. Park, and J.-W. Kim, "Comparison of Gait Patterns in Elderly Fallers and Non-Fallers," *Technology and Health Care* 26, no. 1_suppl. (2018): 427–436, https://doi.org/10.3233/THC-174736.

62. C. V. Ward, "Interpreting the Posture and Locomotion of *Australopithecus afarensis*: Where Do We Stand?," *American Journal of Physical Anthropology* 119, no. S35 (2002): 185–215, https://doi.org/10.1002/ajpa.10185.

63. K. D. Hunt, "The Evolution of Human Bipedality: Ecology and Functional Morphology," *Journal of Human Evolution* 26, no. 3 (1994): 183–202, https://doi.org/10.1006/jhev.1994.1011.

64. C. Leslie, "Terrestriality, Bipedalism and the Origin of Language," paper presented at the Proceedings of the British Academy, 1996.

65. R. R. Provine, "Walkie-Talkie Evolution: Bipedalism and Vocal Production," *Behavioral and Brain Sciences* 27, no. 4 (2004): 520–521, https://doi.org/10.1017/S0140525X04410115.

66. K. J. Ganley and C. M. Powers, "Intersegmental Dynamics During the Swing Phase of Gait: A Comparison of Knee Kinetics Between 7 Year-Old Children and Adults," *Gait & Posture* 23, no. 4 (2006): 499–504, https://doi.org/10.1016/j.gaitpost.2005.06.013.

67. K. Takakusaki, "Functional Neuroanatomy for Posture and Gait Control," *Journal of Movement Disorders* 10, no. 1 (2017): 1, https://doi.org/10.14802/jmd.16062.

68. M. E. Tinetti, M. Speechley, and S. F. Ginter, "Risk Factors for Falls Among Elderly Persons Living in the Community," *New England Journal of Medicine* 319, no. 26 (1988): 1701–1707, 10.1056/NEJM198812293192604.

69. M. H. Schwartz and A. Rozumalski, "The Gait Deviation Index: A New Comprehensive Index of Gait Pathology," *Gait & Posture* 28, no. 3 (2008): 351–357, https://doi.org/10.1016/j.gaitpost.2008.05.001.

70. G. F. Harris and J. J. Wertsch, "Procedures for Gait Analysis," *Archives of Physical Medicine and Rehabilitation* 75, no. 2 (1994): 216–225, https://doi.org/10.1016/0003-9993(94)90399-9.

71. J. Rose and J. G. Gamble, *Human Walking* (Lippincott Williams & Wilkins, 2006).

72. C. Schreiber, A. Remacle, F. Chantraine, E. Kolanowski, and F. Moissenet, "Influence of a Rhythmic Auditory Stimulation on Asymptomatic Gait," *Gait & Posture* 50 (2016): 17–22.

73. S. J. Kim, E. E. Kwak, E. S. Park, et al., "Changes in Gait Patterns With Rhythmic Auditory Stimulation in Adults With Cerebral Palsy," *Neurorehabilitation* 29, no. 3 (2011): 233–241, https://doi.org/10.3233/NRE-2011-0698.

74. S. J. Lee, J. Y. Yoo, J. S. Ryu, H. K. Park, and S. J. Chung, "The Effects of Visual and Auditory Cues on Freezing of Gait in Patients With Parkinson Disease," *American Journal of Physical Medicine & Rehabilitation* 91, no. 1 (2012): 2–11, 10.1097/PHM.0b013e31823c7507.

75. M. H. Schwartz, A. Rozumalski, and J. P. Trost, "The Effect of Walking Speed on the Gait of Typically Developing Children," *Journal of Biomechanics* 41, no. 8 (2008): 1639–1650, https://doi.org/10.1016/j.jbiomech.2008.03.015.

76. S. Ghai, I. Ghai, G. Schmitz, and A. O. Effenberg, "Effect of Rhythmic Auditory Cueing on Parkinsonian Gait: A Systematic Review and Meta-Analysis," *Scientific Reports* 8, no. 1 (2018): 506, https://doi.org/10.1038/s41598-017-16232-5.

77. S. Ghai, I. Ghai, and A. O. Effenberg, "Effect of Rhythmic Auditory Cueing on Gait in Cerebral Palsy: A Systematic Review and Meta-Analysis," *Neuropsychiatric Disease and Treatment* 14 (2017): 43–59, https://doi.org/10.2147/NDT.S148053.

78. A. P. Horin, E. C. Harrison, K. S. Rawson, and G. M. Earhart, "Finger Tapping as a Proxy for Gait: Similar Effects on Movement Variability During External and Self-Generated Cueing in People With Parkinson's Disease and Healthy Older Adults," *Annals of Physical and Rehabilitation Medicine* 64, no. 4 (2021): 101402, https://doi.org/10.1016/j.rehab.2020.05.009.

79. N. Hogan and D. Sternad, "On Rhythmic and Discrete Movements: Reflections, Definitions and Implications for Motor Control," *Experimental Brain Research* 181 (2007): 13–30, https://doi.org/10.1007/s00221-007-0899-y.

80. P.-J. Maes, M. M. Wanderley, and C. Palmer, "The Role of Working Memory in the Temporal Control of Discrete and Continuous Movements," *Experimental Brain Research* 233 (2015): 263–273, https://doi.org/10.1007/s00221-014-4108-5.

81. W. Qi, T. Nakajima, M. Sakamoto, K. Kato, Y. Kawakami, and K. Kanosue, "Walking and Finger Tapping Can be Done With Independent Rhythms," *Scientific Reports* 9, no. 1 (2019): 7620, https://doi.org/10.1038/s41598-019-43824-0.

82. R. T. Krampe, M. Doumas, A. Lavrysen, and M. Rapp, "The Costs of Taking It Slowly: Fast and Slow Movement Timing in Older Age," *Psychology and Aging* 25, no. 4 (2010): 980, https://doi.org/10.1037/a0020090.

83. S. D. Robertson, H. N. Zelaznik, D. A. Lantero, et al., "Correlations for Timing Consistency Among Tapping and Drawing Tasks: Evidence Against a Single Timing Process for Motor Control," *Journal of Experimental Psychology Human Perception and Performance* 25, no. 5 (1999): 1316–1330, 10.1037//0096-1523.25.5.1316.

84. J. Gibbon, "Scalar Expectancy Theory and Weber's Law in Animal Timing," *Psychological Review* 84, no. 3 (1977): 279, https://psycnet.apa.org/doi/10.1037/0033-295X.84.3.279.

85. H. N. Zelaznik, R. M. Spencer, and R. B. Ivry, "Behavioral Analysis of Human Movement Timing," in *Psychology of Time*, ed. S. Grondin (Emerald, 2008), 233–260.

86. R. Huys, B. E. Studenka, N. L. Rheaume, H. N. Zelaznik, and V. K. Jirsa, "Distinct Timing Mechanisms Produce Discrete and Continuous Movements," *PLoS Computational Biology* 4, no. 4 (2008): e1000061, https://doi.org/10.1371/journal.pcbi.1000061.

87. J. D. Loehr, E. W. Large, and C. Palmer, "Temporal Coordination and Adaptation to Rate Change in Music Performance," *Journal of Experimental Psychology: Human Perception and Performance* 37, no. 4 (2011): 1292, https://psycnet.apa.org/doi/10.1037/a0023102.

88. K. Torre and R. Balasubramaniam, "Two Different Processes for Sensorimotor Synchronization in Continuous and Discontinuous Rhythmic Movements," *Experimental Brain Research* 199, no. 2 (2009): 157–166, https://doi.org/10.1007/s00221-009-1991-2.

89. D. Delignières, K. Torre, and L. Lemoine, "Fractal Models for Event-Based and Dynamical Timers," *Acta Psychologica* 127, no. 2 (2008): 382–397, https://doi.org/10.1016/j.actpsy.2007.07.007.

90. M. Sakamoto, T. Tazoe, T. Nakajima, T. Endoh, S. Shiozawa, and T. Komiyama, "Voluntary Changes in Leg Cadence Modulate Arm Cadence During Simultaneous Arm and Leg Cycling," *Experimental Brain Research* 176 (2007): 188–192, https://doi.org/10.1007/s00221-006-0742-x.

91. M. Sakamoto, T. Tazoe, T. Nakajima, T. Endoh, and T. Komiyama, "Leg Automaticity Is Stronger Than Arm Automaticity During Simultaneous Arm and Leg Cycling," *Neuroscience Letters* 564 (2014): 62–66, https://doi.org/10.1016/j.neulet.2014.02.009.

92. S. M. Guérin, M. A. Vincent, and Y. N. Delevoye-Turrell, "Effects of Motor Pacing on Frontal-Hemodynamic Responses During Continuous Upper-Limb and Whole-Body Movements," *Psychophysiology* 60, no. 5 (2023): e14226, https://doi.org/10.1111/psyp.14226.

93. B. H. Repp and R. Doggett, "Tapping to a Very Slow Beat: A Comparison of Musicians and Nonmusicians," *Music Perception* 24, no. 4 (2007): 367–376, https://doi.org/10.1525/mp.2007.24.4.367.

94. B. H. Repp, "Sensorimotor Synchronization and Perception of Timing: Effects of Music Training and Task Experience," *Human Movement Science* 29, no. 2 (2010): 200–213, https://doi.org/10.1016/j.humov.2009.08.002.

95. L. Baer, J. Thibodeau, T. Gralnick, K. Li, and V. Penhune, "The Role of Musical Training in Emergent and Event-Based Timing," *Frontiers in Human Neuroscience* 7 (2013): 191, https://doi.org/10.3389/fnhum.2013.00191.

96. M. Franěk, J. Mates, T. Radil, K. Beck, and E. Pöppel, "Finger Tapping in Musicians and Nonmusicians," *International Journal of Psychophysiology* 11, no. 3 (1991): 277–279, https://doi.org/10.1016/0167-8760(91)90022-P.

97. P. Tranchant, E. Scholler, and C. Palmer, "Endogenous Rhythms Influence Musicians' and Non-Musicians' Interpersonal Synchrony," *Scientific Reports* 12, no. 1 (2022): 12973, https://doi.org/10.1038/s41598-022-16686-2.

98. E. A. Ready, J. D. Holmes, and J. A. Grahn, "Gait in Younger and Older Adults During Rhythmic Auditory Stimulation Is Influenced by Groove, Familiarity, Beat Perception, and Synchronization Demands," *Human Movement Science* 84 (2022): 102972, https://doi.org/10.1016/j.humov.2022.102972.

99. S. Rossignol, R. Dubuc, and J.-P. Gossard, "Dynamic Sensorimotor Interactions in Locomotion," *Physiological Reviews* 86, no. 1 (2006): 89–154, https://doi.org/10.1152/physrev.00028.2005.

100. J. B. Nielsen, "How We Walk: Central Control of Muscle Activity During Human Walking," *Neuroscientist* 9, no. 3 (2003): 195–204, https://doi.org/10.1177/1073858403009003012.

101. Y. Gerasimenko, R. Gorodnichev, E. Machueva, et al., "Novel and Direct Access to the Human Locomotor Spinal Circuitry," *Journal of Neuroscience* 30, no. 10 (2010): 3700–3708, https://doi.org/10.1523/JNEUROSCI.4751-09.2010.

102. M. R. Dimitrijevic, Y. Gerasimenko, and M. M. Pinter, "Evidence for a Spinal Central Pattern Generator in Humans," *Annals of the New York Academy of Sciences* 860, no. 1 (1998): 360–376, https://doi.org/10.1111/j.1749-6632.1998.tb09062.x.

103. A. D. Kuo, "The Six Determinants of Gait and the Inverted Pendulum Analogy: A Dynamic Walking Perspective," *Human Movement Science* 26, no. 4 (2007): 617–656, https://doi.org/10.1016/j.humov.2007.04.003.

104. G. Taga, "Global Entrainment in the Brain–Body–Environment: Retrospective and Prospective Views," *Biological Cybernetics* 115, no. 5 (2021): 431–438, https://doi.org/10.1007/s00422-021-00898-2.

105. F. Alton, L. Baldey, S. Caplan, and M. Morrissey, "A Kinematic Comparison of Overground and Treadmill Walking," *Clinical Biomechanics* 13, no. 6 (1998): 434–440, https://doi.org/10.1016/S0268-0033(98)00012-6.

106. D. Hammerschmidt, K. Frieler, and C. Wöllner, "Spontaneous Motor Tempo: Investigating Psychological, Chronobiological, and Demographic Factors in a Large-Scale Online Tapping Experiment," *Frontiers in Psychology* 12 (2021): 677201, https://doi.org/10.3389/fpsyg.2021.677201.

107. J. Kelso, *Dynamic Patterns: The Self-Organization of Brain and Behavior* (MIT Press, 1995).

108. T. Hanakawa, Y. Katsumi, H. Fukuyama, et al., "Mechanisms Underlying Gait Disturbance in Parkinson's Disease: A Single Photon Emission Computed Tomography Study," *Brain* 122, no. 7 (1999): 1271–1282, https://doi.org/10.1093/brain/122.7.1271.

109. G. Taga, "A Model of the Neuro-Musculo-Skeletal System for Anticipatory Adjustment of Human Locomotion During Obstacle Avoidance," *Biological Cybernetics* 78, no. 1 (1998): 9–17, https://doi.org/10.1007/s004220050408.

110. G. Yogev, M. Plotnik, C. Peretz, N. Giladi, and J. M. Hausdorff, "Gait Asymmetry in Patients With Parkinson's Disease and Elderly Fallers: When Does the Bilateral Coordination of Gait Require Attention?," *Experimental Brain Research* 177, no. 3 (2007): 336–346, https://doi.org/10.1007/s00221-006-0676-3.

111. J. A. Bailey and V. B. Penhune, "Rhythm Synchronization Performance and Auditory Working Memory in Early-and Late-Trained Musicians," *Experimental Brain Research* 204 (2010): 91–101.

112. F. Dege and U. Frischen, "The Impact of Music Training on Executive Functions in Childhood—A Systematic Review," *Zeitschrift für Erziehungswissenschaft* 25, no. 3 (2022): 579–602, https://doi.org/10.1007/s11618-022-01102-2.

113. D. A. Rodriguez-Gomez and C. Talero-Gutierrez, "Effects of Music Training in Executive Function Performance in Children: A Systematic Review," *Frontiers in Psychology* 13 (2022): 968144, https://doi.org/10.3389/fpsyg.2022.968144.

114. K. Jamey, H. Laflamme, N. E. Foster, et al., "Can You Beat the Music? Validation of a Gamified Rhythmic Training in Children With ADHD," *Behavior Research Methods* 57, no. 11 (2025): 1–26, https://doi.org/10.3758/s13428-025-02802-3.

115. A. Biswas, S. Hegde, K. Jhunjhunwala, and P. K. Pal, "Two Sides of the Same Coin: Impairment in Perception of Temporal Components of Rhythm and Cognitive Functions in Parkinson's Disease," *Basal Ganglia* 6, no. 1 (2016): 63–70, https://doi.org/10.1016/j.baga.2015.12.001.

116. A. Diamond, "Executive Functions," *Annual Review of Psychology* 64, no. 1 (2013): 135–168, https://doi.org/10.1146/annurev-psych-113011-143750.

117. K. Jamey, N. E. Foster, K. L. Hyde, and S. Dalla Bella, "Does Music Training Improve Inhibition Control in Children? A Systematic Review and Meta-Analysis," *Cognition* 252 (2024): 105913, https://doi.org/10.1016/j.cognition.2024.105913.

118. C. Y. Wan and G. Schlaug, "Music Making as a Tool for Promoting Brain Plasticity Across the Life Span," *Neuroscientist* 16, no. 5 (2010): 566–577, https://doi.org/10.1177/1073858410377805.

119. G. Sala and F. Gobet, "Cognitive and Academic Benefits of Music Training With Children: A Multilevel Meta-Analysis," *Memory & Cognition* 48, no. 8 (2020): 1429–1441, https://doi.org/10.3758/s13421-020-01060-2.

120. I. Roden, D. Grube, S. Bongard, and G. Kreutz, "Does Music Training Enhance Working Memory Performance? Findings From a Quasi-Experimental Longitudinal Study," *Psychology of Music* 42, no. 2 (2014): 284–298, https://doi.org/10.1177/0305735612471239.

121. R. Román-Caballero, M. A. Vadillo, L. J. Trainor, and J. Lupianez, "Please Don't Stop the Music: A Meta-Analysis of the Cognitive and Academic Benefits of Instrumental Musical Training in Childhood and Adolescence," *Educational Research Review* 35 (2022): 100436, https://doi.org/10.1016/j.edurev.2022.100436.

122. E. Bigand and B. Tillmann, "Near and Far Transfer: Is Music Special?," *Memory & Cognition* 50, no. 2 (2022): 339–347, https://doi.org/10.3758/s13421-021-01226-6.

123. J. A. Bugos, W. M. Perlstein, C. S. McCrae, T. S. Brophy, and P. H. Bedenbaugh, "Individualized Piano Instruction Enhances Executive Functioning and Working Memory in Older Adults," *Aging and Mental Health* 11, no. 4 (2007): 464–471, https://doi.org/10.1080/13607860601086504.

124. J. A. Bugos and Y. Wang, "Piano Training Enhances Executive Functions and Psychosocial Outcomes in Aging: Results of a Randomized

Controlled Trial," *Journals of Gerontology: Series B* 77, no. 9 (2022): 1625–1636, https://doi.org/10.1093/geronb/gbac021.

125. S. Seinfeld, H. Figueroa, J. Ortiz-Gil, and M. V. Sanchez-Vives, "Effects of Music Learning and Piano Practice on Cognitive Function, Mood and Quality of Life in Older Adults," *Frontiers in Psychology* 4 (2013): 810, https://doi.org/10.3389/fpsyg.2013.00810.

126. V. N. Salimpoor, D. H. Zald, R. J. Zatorre, A. Dagher, and A. R. McIntosh, "Predictions and the Brain: How Musical Sounds Become Rewarding," *Trends in Cognitive Sciences* 19, no. 2 (2015): 86–91, https://doi.org/10.1016/j.tics.2014.12.001.

127. V. Krause, B. Pollok, and A. Schnitzler, "Perception in Action: The Impact of Sensory Information on Sensorimotor Synchronization in Musicians and Non-Musicians," *Acta Psychologica* 133, no. 1 (2010): 28–37, https://doi.org/10.1016/j.actpsy.2009.08.003.

128. T. E. Matthews, J. N. Thibodeau, B. P. Gunther, and V. B. Penhune, "The Impact of Instrument-Specific Musical Training on Rhythm Perception and Production," *Frontiers in Psychology* 7 (2016): 69, https://doi.org/10.3389/fpsyg.2016.00069.

129. R. Vathagavorakul, T. Gonjo, and M. Homma, "Differences in Limb Coordination in Polyrhythmic Production Among Water Polo Players, Artistic Swimmers and Drummers," *Journal of Motor Behavior* 53, no. 2 (2021): 191–199, https://doi.org/10.1080/00222895.2020.1748860.

130. B. Bonnechère, B. Jansen, L. Omelina, and S. V. S. Jan, "The Use of Commercial Video Games in Rehabilitation: A Systematic Review," *International Journal of Rehabilitation Research* 39, no. 4 (2016): 277–290, https://doi.org/10.1097/MRR.0000000000000190.

131. V. Bégel, A. Seilles, and S. Dalla Bella, "Rhythm Workers: A Music-Based Serious Game for Training Rhythm Skills," *Music & Science* 1 (2018): 2059204318794369.

132. A. Nieuwboer, G. Kwakkel, L. Rochester, et al., "Cueing Training in the Home Improves Gait-Related Mobility in Parkinson's Disease: The RESCUE Trial," *Journal of Neurology, Neurosurgery & Psychiatry* 78, no. 2 (2007): 134–140, https://doi.org/10.1136/jnnp.200X.097923.

133. M. H. Thaut, G. C. McIntosh, R. R. Rice, R. A. Miller, J. Rathbun, and J. M. Brault, "Rhythmic Auditory Stimulation in Gait Training for Parkinson's Disease Patients," *Movement Disorders: Official Journal of the Movement Disorder Society* 11, no. 2 (1996): 193–200, https://doi.org/10.1002/mds.870110213.

134. T. Braun Janzen, Y. Koshimori, N. M. Richard, and M. H. Thaut, "Rhythm and Music-Based Interventions in Motor Rehabilitation: Current Evidence and Future Perspectives," *Frontiers in Human Neuroscience* 15 (2022): 789467, https://doi.org/10.3389/fnhum.2021.789467.

135. P. A. Rocha, G. M. Porfírio, H. B. Ferraz, and V. F. Trevisani, "Effects of External Cues on Gait Parameters of Parkinson's Disease Patients: A Systematic Review," *Clinical Neurology and Neurosurgery* 124 (2014): 127–134, https://doi.org/10.1016/j.clineuro.2014.06.026.

136. V. A. Goodwin, S. H. Richards, R. S. Taylor, A. H. Taylor, and J. L. Campbell, "The Effectiveness of Exercise Interventions for People With Parkinson's Disease: A Systematic Review and Meta-Analysis," *Movement Disorders* 23, no. 5 (2008): 631–640, https://doi.org/10.1002/mds.21922.

137. L. Mochizuki, A. Bigongiari, P. M. Franciulli, et al., "The Effect of Gait Training and Exercise Programs on Gait and Balance in Post-Stroke Patients," *MedicalExpress* 2, no. 4 (2015): M150401, https://doi.org/10.5935/MedicalExpress.2015.04.01.

138. E. J. Protas, K. Mitchell, A. Williams, H. Qureshy, K. Caroline, and E. C. Lai, "Gait and Step Training to Reduce Falls in Parkinson's Disease," *Neurorehabilitation* 20, no. 3 (2005): 183–190, https://doi.org/10.3233/NRE-2005-20305.

139. I. Lim, E. van Wegen, C. de Goede, et al., "Effects of External Rhythmical Cueing on Gait in Patients With Parkinson's Disease: A Systematic Review," *Clinical Rehabilitation* 19, no. 7 (2005): 695–713, https://doi.org/10.1191/0269215505cr906oa.

140. A. Nieuwboer, K. Baker, A.-M. Willems, et al., "The Short-Term Effects of Different Cueing Modalities on Turn Speed in People With Parkinson's Disease," *Neurorehabilitation and Neural Repair* 23, no. 8 (2009): 831–836, https://doi.org/10.1177/1545968309337136.

141. S. Prassas, M. Thaut, G. McIntosh, and R. Rice, "Effect of Auditory Rhythmic Cuing on Gait Kinematic Parameters of Stroke Patients," *Gait & Posture* 6, no. 3 (1997): 218–223, https://doi.org/10.1016/S0966-6362(97)00010-6.

142. N. de Bruin, J. B. Doan, G. Turnbull, et al., "Walking With Music Is a Safe and Viable Tool for Gait Training in Parkinson's Disease: The Effect of a 13-Week Feasibility Study on Single and Dual Task Walking," *Parkinson's Disease* 2010, no. 1 (2010): 483530, https://doi.org/10.4061/2010/483530.

143. M. H. Thaut, R. R. Rice, T. Braun Janzen, C. P. Hurt-Thaut, and G. C. McIntosh, "Rhythmic Auditory Stimulation for Reduction of Falls in Parkinson's Disease: A Randomized Controlled Study," *Clinical Rehabilitation* 33, no. 1 (2019): 34–43, https://doi.org/10.1177/0269215518788615.

144. M. F. del Olmo and J. Cudeiro, "Temporal Variability of Gait in Parkinson disease: Effectsof a Rehabilitation Programme Based on Rhythmic Sound Cues," *Parkinsonism & Related Disorders* 11, no. 1 (2005): 25–33, https://doi.org/10.1016/j.parkreldis.2004.09.002.

145. C. C. Harro, M. J. Shoemaker, O. J. Frey, et al., "The Effects of Speed-Dependent Treadmill Training and Rhythmic Auditory-Cued Overground Walking on Gait Function and Fall Risk in Individuals With Idiopathic Parkinson's Disease: A Randomized Controlled Trial," *Neurorehabilitation* 34, no. 3 (2014): 557–572, https://doi.org/10.3233/NRE-141051.

146. Z. Kadivar, D. M. Corcos, J. Foto, and J. M. Hondzinski, "Effect of Step Training and Rhythmic Auditory Stimulation on Functional Performance in Parkinson Patients," *Neurorehabilitation and Neural Repair* 25, no. 7 (2011): 626–635, https://doi.org/10.1177/1545968311401627.

147. R. De Icco, C. Tassorelli, E. Berra, M. Bolla, C. Pacchetti, and G. Sandrini, "Acute and Chronic Effect of Acoustic and Visual Cues on Gait Training in Parkinson's Disease: A Randomized, Controlled Study," *Parkinson's Disease* 2015, no. 1 (2015): 978590, https://doi.org/10.1155/2015/978590.

148. M. Murgia, R. Pili, F. Corona, et al., "The Use of Footstep Sounds as Rhythmic Auditory Stimulation for Gait Rehabilitation in Parkinson's Disease: A Randomized Controlled Trial," *Frontiers in Neurology* 9 (2018): 348, https://doi.org/10.3389/fneur.2018.00348.

149. D. G. Dotov, V. Cochen De Cock, C. Geny, et al., "The Role of Interaction and Predictability in the Spontaneous Entrainment of Movement," *Journal of Experimental Psychology: General* 148, no. 6 (2019): 1041, https://doi.org/10.1037/xge0000609.

150. A. Zagala, N. E. Foster, F. T. van Vugt, F. Dal Maso, and S. Dalla Bella, "The Ramp Protocol: Uncovering Individual Differences in Walking to an Auditory Beat Using TeensyStep," *Scientific Reports* 14, no. 1 (2024): 23779, https://doi.org/10.1038/s41598-024-72508-7.

151. J. A. Zajac, F. Porciuncula, J. T. Cavanaugh, et al., "Feasibility and Proof-of-Concept of Delivering an Autonomous Music-Based Digital Walking Intervention to Persons With Parkinson's Disease in a Naturalistic Setting," *Journal of Parkinson's Disease* 13, no. 7 (2023): 1253–1265, https://doi.org/10.3233/JPD-230169.

152. V. Cochen De Cock, D. Dotov, L. Damm, et al., "BeatWalk: Personalized Music-Based Gait Rehabilitation in Parkinson's Disease," *Frontiers in Psychology* 12 (2021): 655121, https://doi.org/10.3389/fpsyg.2021.655121.

153. F. T. van Vugt, "The TeensyTap Framework for Sensorimotor Synchronization Experiments," *Advances in Cognitive Psychology* 16, no. 4 (2020): 302, https://doi.org/10.5709/acp-0304-y.

154. D. Gorjan, K. Gramann, K. De Pauw, and U. Marusic, "Removal of Movement-Induced EEG Artifacts: Current State of the Art and Guidelines," *Journal of Neural Engineering* 19, no. 1 (2022): 011004, https://doi.org/10.1088/1741-2552/ac542c.

155. R. Huang, K.-S. Hong, D. Yang, and G. Huang, "Motion Artifacts Removal and Evaluation Techniques for Functional Near-Infrared Spectroscopy Signals: A Review," *Frontiers in Neuroscience* 16 (2022): 878750, https://doi.org/10.3389/fnins.2022.878750.

156. M. Seeber, R. Scherer, J. Wagner, T. Solis-Escalante, and G. R. Müller-Putz, "High and Low Gamma EEG Oscillations in Central Sensorimotor Areas Are Conversely Modulated During the Human Gait Cycle," *Neuroimage* 112 (2015): 318–326.

157. M. Klug and N. A. Kloosterman, "Zapline-Plus: A Zapline Extension for Automatic and Adaptive Removal of Frequency-Specific Noise Artifacts in M/EEG," *Human Brain Mapping* 43, no. 9 (2022): 2743–2758, https://doi.org/10.1002/hbm.25832.

158. I. Maidan, D. Patashov, S. Shustak, et al., "A New Approach to Quantifying the EEG During Walking: Initial Evidence of Gait Related Potentials and Their Changes With Aging and Dual Tasking," *Experimental Gerontology* 126 (2019): 110709.

159. M. Seeber, R. Scherer, J. Wagner, T. Solis-Escalante, and G. R. Müller-Putz, "EEG Beta Suppression and Low Gamma Modulation Are Different Elements of Human Upright Walking," *Frontiers in Human Neuroscience* 8 (2014): 485.

160. J. Wagner, S. Makeig, M. Gola, C. Neuper, and G. Müller-Putz, "Distinct β Band Oscillatory Networks Subserving Motor and Cognitive Control During Gait Adaptation," *Journal of Neuroscience* 36, no. 7 (2016): 2212–2226, https://doi.org/10.1523/JNEUROSCI.3543-15.2016.

161. S. Makeig, K. Gramann, T.-P. Jung, T. J. Sejnowski, and H. Poizner, "Linking Brain, Mind and Behavior," *International Journal of Psychophysiology* 73, no. 2 (2009): 95–100, https://doi.org/10.1016/j.ijpsycho.2008.11.008.