The Connection Between Rhythmicity and Brain Function

Implications for Therapy of Movement Disorders

Eliciting physical response has been described in music anthropology as one of the 10 basic functions of music in human culture [1]. Throughout history, music, especially through the temporal element of rhythm, has stimulated and shaped physical response in different societal contexts, such as during movement and dance rituals as part of religious, social, and political ceremonies; in movement performance for aesthetic expression and entertainment; or for coordination of people’s physical efforts during work tasks [1]. Traditionally, music psychology has viewed and interpreted the effect of music on physical response from motivational, emotional, and aesthetic points of view. Not until very recently have scientists begun to unravel the very intricate and substantial connections between sound and movement from a physiological point of view. And only within the last few years have some fascinating applications, specifically of the rhythmic structures of sound to motor rehabilitation, been discovered.

The physiological mechanisms for this connection are based on the interactions between the auditory and motor systems. From the pathbreaking research of Paltsiev and Elner [2] and Rossignol and Melvill Jones [3] we know that sound can arouse and raise the excitability of spinal motor neurons mediated by auditory-motor circuitry at the reticulo-spinal level. Furthermore, it was demonstrated [3] that rhythmically structured sound patterns, such as in a simple dance tune in 2/4 meter, can entrain the timing of muscle activation patterns, as measured by electromyography (EMG), and thus facilitate movement during rhythmic hopping movements. It is also well known that the auditory system is an extremely fast processor of sensory information, based on the necessity to capture and extract meaning from sensory information that is physically present only as a dynamic temporal waveform process with rapid time decay. Sound patterns, unlike visual and other sensory information, continuously unfold and change in time, and cannot be “frozen” in time and space for a retroactive analysis.

Based on these features, an interesting dynamic parallel between the temporal nature of auditory information and movement performance arises. This relationship is also physiologically manifested in observations that auditory cues create consistently 20-50 msec faster physical reaction times than do visual or tactile cues [4, 5] and that the perception and motoric reproduction of time patterns are more stable, accurate, and faster acoustically than in other sense modalities [6].

In this article we first present some clinical research results involving rhythmic facilitation and motor control. We then discuss synchronization strategies for sensorimotor coupling pertaining to rhythmic entrainment mechanisms; followed by trajectory cuing and optimization models as they relate to rhythmic entrainment and movement control; and, finally, the outlook for applications that may help rehabilitate motor function. Our interest in the study of the connections between rhythm, time, and the control of movement was stimulated from three directions: a) the study of high-level motor control in musicians [7] and the effect of rhythmic cues on muscle activity in cello performance [8]; b) the evidence that auditory rhythmic patterns exert a strong “magnet” effect on the timing of motor responses (see [9] for a review); and c) the clinical observation that music-therapy techniques that were originally designed for socio-emotional needs...
The presence of rhythmic cues adds stability in motor control immediately.

elicited motor responses in neurollogically impaired patients that were not readily accessible by other therapies [10].

Clinical Research: Rhythmic Facilitation and Motor Control

In our initial clinical investigations, we selected stroke patients with hemiparetic gait patterns to study the effect of rhythm on motor control. We reasoned that if rhythm had any effect on gait it might be most clearly demonstrable in the restoration of symmetry in hemiparetic gait patterns. In a study with 10 hemispheric stroke patients (four weeks to 24 months poststroke), the frequency of the metronome in a simple instrumental composition (from the Renaissance period) was matched to the step rate of the patients. Walking with and without rhythmic cuing was counterbalanced to avoid simple practice effects. Two retests were conducted over a period of five weeks to determine if the results of providing rhythmic cuing could be replicated. As in all subsequent movement studies, movement parameters were assessed with EMG, digital three-dimensional (3-D) video motion analysis, and computerized footsensors for stride analysis.

The results showed that effects of rhythmic auditory stimulation (RAS) were very pronounced. In all cases, rhythmic cuing produced large statistically significant improvements in stride symmetry, weightbearing period on the paretic leg, knee angle control, and mediolateral and vertical displacement of center of mass resulting in a smoother forward trajectory of movement [11, 12]. The kinematic effects were accompanied by physiological changes showing that auditory rhythm entrained higher symmetry and reduced variability in EMG patterns of the gastrocnemius muscle in both legs.

An experiment that studied the immediate entrainment effect of rhythm on movement, without practice and learning, strongly suggested that RAS had a comprehensive spatiotemporal effect on improvement of the total pattern of gait. The results from these experiments led to two main directions of research: a) the study of mechanisms connecting rhythm to motor control, which will be discussed below, and b) applications of the observed immediate entrainment effect to longer-term therapy studies. A six-week clinical rehabilitation therapy study with 20 stroke patients showed that the gait improvements through RAS were sustained, and that the gains in gait performance were statistically higher than gains from conventional physical therapy, with the largest area of improvement being gait velocity [13].

These studies indicated that gait, as an intrinsically rhythmic movement, is very accessible to rhythmic sensory cuing to attain performance improvements. However, two interesting and urgent questions emerged from this research. First, the profound effect of rhythm as a timing cue, not only on the temporal aspects of movement, but on the total spatiotemporal pattern of gait, needed further elaboration. The second question pertained to whether RAS could also facilitate arm movement, although arm movements are for the most part not controlled by intrinsically rhythmic central pattern generators, as is gait. The second question has added therapeutic significance because, in stroke patients, recovery of arm function is often more resistant to therapeutic efforts than recovery of gait ability.

To answer the latter question, we recently studied rhythmic facilitation of the paretic arm in stroke patients. The experiment consisted of a simple continuous sequence of reaching movements for 30 sec, in which each repetition was supposed to be performed as evenly as possible [14]. The results showed, very impressively, that timing of the reaching movements was considerably less variable with rhythm than without rhythm. Moreover, the 3-D trajectory of the reaching motion of the arm was also more consistent, again showing that rhythm affects the total movement pattern and not just timing of movement. This was also evidenced by the fact that elbow range of motion increased significantly during rhythmically cued reaching.

An interesting clue as to how rhythm cues movement emerged from a movement-by-movement analysis across trial time. Improved spatiotemporal arm control was already evident during the first few reaching movements at the outset of the rhythmic trial, after the patient had just heard two metronome beats prior to the beginning of movement. This improved performance status at the beginning of the movement task indicated impressively that the presence of rhythmic cues adds stability in motor control immediately, rather than through a gradual learning process. In the following sections, evidence will be provided that this stability is probably mediated by an immediate

![Parkinson's Disease Gait Decline Study](image)

1. Averaged gait velocity profiles for 22 PD subjects at pretest, post-test after three weeks of RAS training, and five weekly follow-up tests without training (F1 to F5). Clearly noticeable is the strong decline at F4.
rhythmic synchronization process between the metronome and the movement response [15]. The time-adaptation mechanisms underlying this process strongly suggest the existence of direct sensory-motor coupling processes, in which sensory information drives motor action directly, without cognitive adaptation or learning processes. Strong support for profound changes in motor control strategies during rhythmic cuing was further provided by an analysis of the velocity and acceleration profiles of the arm movement, which showed considerable smoothing in shape when rhythmic cues were present.

A similar line of research, employing entrainment and therapy designs as experimental protocols, was pursued in subsequent studies with patients with Parkinson’s disease (PD). In experiments studying immediate rhythmic entrainment of gait, without training it was found that PD patients were able to synchronize their step patterns to metronome and rhythmic music cues, which is very similar to the way healthy elderly persons respond. Interestingly, the synchronization ability was also retained when PD patients had gone off their dopaminergic medication for 24 to 48 hours, showing that deficient function of the basal ganglia structures in the brain does not substantially alter the ability of rhythmic tracking [16].

The therapeutic importance of these findings was evidenced by the fact that rhythmic synchronization improved stride symmetry as well as entrained higher step cadence and stride length, resulting in more normalized gait parameters. Again, these immediate facilitation effects of rhythm were sustained in a three-week training application and were shown to be significantly higher than gains from gait training during regular physical therapy [17]. A nine-week follow up after three weeks of RAS training showed that gains from rhythm were maintained for about a month before significant decline set in (Fig. 1) [18].

The physiological effect of rhythm on motor control in gait was also substantiated with PD patients by studying symmetry and variability of timing and magnitude in the EMGs of the gastrocnemius and anterior tibialis muscles, which are intricately involved in lower limb control throughout the whole stride cycle. The symmetric pulse pattern of the metronome and the metric accents in the music increased the symmetry of muscle activation. Furthermore, the even timing of the rhythmic stimulus significantly reduced variability in the EMG of the two lower leg muscles, indicating improved consistency in the recruitment of motor units (spinal motor neurons and innervated muscle fibers) [19].

Thus, the early findings of Paltsev and Elner [2] and Rossignol and Melvill Jones [3] regarding the physiological receptivity of the motor system to auditory rhythmic input, probably via reticulo-spinal pathways, have been impressively substantiated in our studies with stroke and PD patients. Similar results have also been demonstrated in gait with normal persons [20] and in studies with patients with traumatic brain injury [21] and Huntington’s disease [22].

**Multiple Synchronization Strategies for Sensorimotor Coupling**

The clinical studies described above have two features in common: (a) patients were able, in spite of very differing neuropathologies, to synchronize their motor responses to the auditory rhythm with relative ease; and (b) the performed movements were biologically rhythmic in nature (central pattern generators in gait) or rhythmically organized (sequential arm-reaching movements within a set time structure). Thus, in order to elucidate the mechanisms involved in rhythmic facilitation, an understanding of rhythmic synchronization mechanisms is foundational.

Rhythmic synchronization of motor responses has been studied for almost 100 years, mostly in finger-tapping experiments, due to the relative ease with which the long data sequences necessary to achieve statistical stability can be generated. Although rhythmic synchronization appears quite easy to perform, the issues of variability and dependency in the rhythmic responses are complex and have attracted much research attention [23]. The task in rhythmic synchronization is deceptively simple: to track a rhythmic stimulus with zero time deviations between the response interval and the stimulus interval (period error), and zero time deviations between the occurrence of the rhythmic stimulus and the motor response (phase error). However, due to various noise factors in the perception and production of the rhythm, zero deviations are not possible. Thus, statistical analysis of period and

2. Schematic display of a synchronized motor response adaptation after the period of an isochronous rhythmic stimulus (ISI) is increased at a random point in the sequence. The two possible adaptation responses are graphed below: a) IRI adaptation in which the response interval is reset to the new ISI and a larger SE is temporarily tolerated; b) SE adaptation in which an overcorrected IRI restores the previous SE along with resetting the new ISI.
phase corrections has been used to elucidate adaptation strategies to maintain synchronization. Variability analysis shows that in tracking of rhythmic auditory stimuli, a steady state of tracking behavior is achieved very rapidly, within two or three stimuli. This indicates that a stable temporal template or reference interval is produced in the brain rather quickly. The anticipatory nature of rhythmic tracking, owing to the predictability of the stimulus, is shown by synchronization responses that are usually slightly ahead of the synchronizing stimulus [9]. This phenomenon has been observed in the tracking of musical rhythms as well as single metronome sequences [24].

Most synchronization models have assumed a phase correction mechanism as the primary synchronization strategy [25, 26]. However, employing random step changes in metronome sequences (Fig. 2), an analysis of correction mechanisms has shown that in small changes—within the noise boundaries of normal tracking variability, which range around 5% of the stimulus interval—period errors are corrected first, and then phase errors are gradually recovered. A nonlinear change in correction strategy occurs for larger step changes, beyond the normal variability threshold, where the original phase error is recovered first by temporarily overcorrecting the period (Fig. 3) [27]. These results have been replicated for pulse changes and for musical rhythms [28].

Thus, multiple synchronization strategies can be proposed that are dependent on the dynamical state of the synchronizing system and that reflect nonlinear processes in rhythmic tracking. The dominant synchronization strategy for small or steady-state tracking seems to be based on absolute time matching between stimulus and response period, and not phase error corrections; i.e., the evidence strongly favors frequency-entrainment strategies rather than phase entrainment. We have developed a simple computational model that determines timing of each synchronized motor response as the sum of an internal reference interval (RI) and a control term (C), depending on stimulus interval duration (SI) and synchronization error (SE), in the form of a recursive equation (n = number of stimuli)

\[ R_{n+1} = R_n + C(SI_n, SE_n) \]

The control term \( C(SI, SE) \) consists of (a) a proportional response to \( SE \), (b) a differentiating response detecting the velocity of change in \( SE \), and (c) an integrating response that reacts to the moving average of \( SE \), such as a traditional PID-controller. The differentiating con-
controller provides the adaptation of R1 to SI, and the integrating controller causes the phase shift to compensate for SE. The model has two main attributes: (a) a hierarchical organization of control strategies prioritizing period adaptation relative to SE compensation and (b) weak coupling of oscillators, which helps to explain how exact control of rhythmic synchronization can be achieved in a fuzzy biological system [27, 29].

Period, rather than phase synchronization, as the dominant rhythmic strategy has enormous consequences for an understanding of the role of rhythm as a movement cue, as will be shown in more detail below. The second dominant observation in rhythmic synchronization (i.e., the ease with which auditory rhythm induces a steady state of synchronized motor responses) can be elucidated with experiments using subliminal and consciously perceptible perturbation patterns.

Subjects tracked a metronome pattern that was continuously modulated following a cosine wave pattern. The results demonstrated that even at perturbation levels close to and below the threshold of awareness (1% and 3% of a base interval of 500 msec) the finger-tapping response followed the dynamics of the stimulus pattern; i.e., the response curves were synchronized within 2-3 repetitions to the stimulus pattern of lag one [15]. The shape congruence of the response pattern to the rhythmic stimulus pattern showed very clearly that the sensory information of the auditory rhythm was able to drive dynamically the synchronization pattern of the motor response. The direct coupling effect of sensory to motor processes was impressively manifested by the fact that these rhythmic entrainment processes were even observable at subliminal perturbation stages, in which conscious perception and corrections of tracking errors were not possible. The subliminality of this process was further substantiated by the fact that the study subjects continued to tap before the metronome beat. The subsequent period correction at lag one, however, also shows the limitations of direct sensory-motor coupling, because at this level of sensorimotor processing, the brain apparently never did recognize the repetition pattern or periodicity in the perturbed metronome. Simple mathematical modeling of the expected error showed that a direct sensory-tracking model had the smallest error compared to models where the perturbation pattern was either not perceived and thus ignored or was anticipated.

In conclusion, several important characteristics of rhythmic synchronization behavior have emerged that point the way toward an understanding of the role of rhythm in motor control:

- Auditory rhythm very rapidly creates stable internal reference intervals to guide the timing of motor responses.
- The motor system is physiologically very sensitive to arousal by the auditory system.
- The neural impulses of auditory rhythm access and stimulate neural motor impulses, which tend to be attracted to and lock into (i.e., become entrained to) the auditory signal frequency. This process can be modeled well through coupled oscillator functions.
- The auditory-motor entrainment process can take place at subliminal levels of sensory perception.
- The dominant synchronization strategy is based on frequency entrainment (i.e., period matching between stimulus and response), whereas phase corrections fluctuate more freely within certain threshold boundaries once a preferred synchronization error has been set.

Trajectory Cuining and Optimization Models

The evidence that rhythmic motor synchronization is primarily driven by frequency entrainment or period matching suggests that rhythm provides time information across the total duration of the movement, and not just at the endpoints of movement when a response is matched to the occurrence of the rhythmic signal (Fig. 4). The research discussed above has provided ample evidence that rhythmic cuing enhances the consistency of timing in arm and gait movements. However, there has also been very strong evidence that non-temporal movement parameters, such as stride length in gait or movement trajectories of upper and lower limb joints (e.g., wrist, knee) improved during rhythmic cuing. Apparently, then, enhanced time stability across the duration of the movement during rhythmic cuing also enhances spatial control of movement.

However, until very recently, a conceptual link was missing to connect time cuing to spatio-dynamic parameters of motor control, before analyses of acceleration and velocity profiles offered an intriguing explanation. The consistent evidence for smoothing of velocity and acceleration profiles of joint motions during rhythmic cuing suggests that rhythm enhances the control of velocity and acceleration by scaling movement time. Velocity and acceleration are time derivatives of position. Thus, in working our theory backwards, we reasoned that by fixing time through a rhythmic interval, for a movement from point A to point B, the subject's internal timekeeper now has a precise reference interval, with time information present at any stage of the movement. This time information will allow the brain to map and scale smoother time parameters of position change (i.e., velocity and acceleration) across the entire movement interval (e.g., heelstrike to heelstrike in gait, reaching the arm from one point to another in space, etc.)

Changes in velocity and acceleration profiles, however, must be reflected in changes in the position-time curve of the movement. This can actually be described mathematically as an optimization problem. If we assume that the brain uses some optimization strategy to control movement, it is indeed possible to show, in certain cases, such that such optimization implies the scaling over time of the resulting movement. The immediate consequence of this assertion is that matching the period of a cyclical movement to the period of an external rhythmic stimulus results in the regulation of the entire movement trajectory. Once the time constraint of rhythm is added, the brain is presented
with a well-defined optimization problem: how to move from point A to point B in a fixed time interval while minimizing some objective function that relates to the body’s cost in making such movement.

A variety of optimization criteria for movement control have been proposed, related to minimizing various cost functions of movement; e.g., movement time, maximum force, impulse energy, mean square jerk, torque change, some forms of total energy cost, etc. [30-32]. In a recent study of paretic arm movements of stroke patients, we have applied minimization of peak absolute acceleration over the entire movement cycle as an optimization criterion for maximizing smoothness of arm trajectories [14]. Since force is proportional to translational acceleration (Newton’s Second Law), and joint torque is proportional to angular acceleration, there is an immediate link between applied muscle force and the resulting movement acceleration required to produce the desired movement. In a one-dimensional case, such minimization of peak absolute acceleration results in a unique acceleration-time curve over the movement cycle.

Once the acceleration history is known, both the velocity-time and the position-time curves are known. Thus, application of this particular optimization criterion implies that the limb position is known throughout the cycle. Therefore, the body’s attempt to optimize its movement may be expected to produce more consistent kinematic results with rhythmic cuing than without rhythm, as long as the internal timekeeper function is not sufficient for optimal control. (Figure 5 shows wrist recordings from a stroke patient’s paretic arm during a reaching movement involving consecutive flexion-extension motions of the elbow.) This helps to explain why rhythmic effects are especially pronounced in our clinical research with various motor neuropathologies, clearly demonstrating that timing is a fundamental parameter in motor control.

Other optimization criteria may be also enhanced by rhythmic entrainment. Based on the observation that the body selects a natural optimal frequency to optimize metabolic cost (for example, during locomotion), rhythmic frequency entrainment to the internal step cadence of a patient may initially stabilize the internal limit cycle of the central gait pattern oscillator [33]. Once this optimization has been established, entrainment into higher step frequencies closer to the premorbid natural gait cadence may result in further normalization of gait parameters and reduction of metabolic cost function, as long as the neurological and mechanical constraints of the motor system are not violated. Such a step-wise limit cycle entrainment (SLICE) process for movement optimization could be easily modeled as a frequency-entrained forced harmonic oscillator (FEFHA) function.

In conclusion, it is at least a fascinating hypothetical suggestion awaiting more experimental validation that, due to the strong physiological attractor function of rhythmic cues on motor response, rhythm actually acts as a forcing function in motor control to optimize kinematic movement parameters, as well as other possible energy cost functions, involved in a given movement.

**Outlook**

Although clinical data and the mathematical analysis of rhythmic behavior allow some conclusions about cerebral processes involved in rhythm and motor control, direct neuroanatomical knowledge about brain regions involved in rhythmic processes is still very limited. Research with patients with specific lesions has until very recently provided the most knowledge. For example, Ivy and Keele’s [34] research has implicated the cerebellum in timing control. Harrington, Haaland, and Hermanowicz [35] have also

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5. Position, velocity, and acceleration parameters of the x-component of the wrist marker during a reaching movement of a stroke patient with the hemiparetic arm with rhythm (left) and without rhythm (right). The smoother position profile is reflected in smoother velocity and acceleration graphs during rhythm. The dashed line in the acceleration graph represents the optimized acceleration under criterion that peak absolute acceleration is minimal. The actual deviation from the optimal in this graph is 38.7% for rhythm and 168.2% without rhythm, indicating a much more optimal trajectory and smoother acceleration curve during rhythmic entrainment.
shown involvement of cerebellar and basal ganglia structures in time perception. However, our studies with PD patients off medication [16] strongly suggest that the basal ganglia is probably not involved in the precise timing of synchronization processes directly, but possibly more in sequencing of rhythmic events.

Within the cerebellum it may be assumed that its lateral and vermal parts might play different roles in rhythmic control. The lateral structures have been found to be involved in higher-level processing of sensory information and motor planning, although recent evidence extends cerebellar activity also to purely sensory and cognitive functions. The vermal structures are known to process auditory information on a more arousal-oriented level; e.g., in the startle reflex [36]. Within cortical areas, parieto-temporal regions, including the insula and thalamic structures, have recently been shown to play a crucial role in rhythmic synchronization during finger tapping to a metronome. Interestingly to note is that these networks seem hemispherically dissociated from the auditory and motor areas involved in listening to the tone and controlling hand movement. Also, these networks do not involve prefrontal areas typically involved in higher-level cognitive and perceptual processes, unless rhythmic tracking tasks with higher sensory load are performed, involving different degrees of perceptual consciousness. We have found strong evidence that these neural networks specific to the planning and execution of rhythmic synchronization are distributed most prominently within the right brain hemisphere [37, 38].

As brain imaging technology is rapidly improving and becoming more accessible, we will also see an exponential growth in knowledge about the neuroanatomical organization of cerebral processes involved in rhythm perception, rhythm production, rhythmic synchronization, and applications of rhythm to facilitate motor control and rehabilitate motor function.

Summary

Although rhythm and music are not entirely synonymous terms, rhythm constitutes one of the most essential structural and organizational elements of music. When considering the effect of music on human adaptation, the profound effect of rhythm on the motor system strongly suggests that the time structure of music is the essential element relating music specifically to motor behavior. Why the motor system appears so sensitive to auditory priming and timing stimulation can only be partially answered so far. The high-performance function of the auditory system regarding processing of time information makes good functional sense within the constraints of auditory sensory processing. Thus, the motor system sensitivity to auditory entrainment may simply be an evolutionary useful function of taking advantage of the specific and unique aspects of auditory information processing for enhanced control and organization of motor behavior; e.g., in the time domain. Unlike processes in the motor system, many other physiological processes cannot be effectively entrained by external sensory stimuli. For example, there is probably a very good protective reason why other cyclical physiological processes (e.g., autonomic processes such as heart rate) have only very limited entrainment capacity to external rhythmic cues. Some of the basic auditory-motor arousal connections may also have their basis in adaptive evolutionary processes related to survival behavior; e.g., in fight or flight reactions. Much of the “why” in auditory-motor interactions, however, remains unknown heuristically. In the absence of this knowledge, great care should be taken to not compensate for this lack of understanding of specific cause and effect processes by assigning anthropomorphic descriptions to the behavior of biological and physical systems.

The unraveling of the perceptual, physiological, and neuroanatomical basis of the interaction between rhythm and movement has been, and continues to be, a fascinating endeavor with important ramifications for the study of brain function, sensory perception, and motor behavior. One of the most exciting findings in this research, however, may be the evidence that the interaction between auditory rhythm and physical response can be effectively harnessed for specific therapeutic purposes in the rehabilitation of persons with movement disorders.

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Temporal Stride Parameters and EMG Patterns in Normal Gait

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